The Ohio State University
Seventh International Symposium on Aviation Psychology

An Approach to Modeling Pilot Memory and Developing a Taxonomy of Memory Errors

Susan J. Mangold
& Donald Eldredge

April 27, 1993

NASA Aviation Safety Reporting System
625 Ellis St. • Suite 305 • Mountain View • California • 94043

ASRS

NASA ASRS (Pub. 48)

AN APPROACH TO MODELING PILOT MEMORY AND DEVELOPING A TAXONOMY OF MEMORY ERRORS

Susan J. Mangold and Donald Eldredge
Battelle
Columbus, Ohio

Incidents that involve the remembering and forgetting of critical flight information by pilots are often found in the Aviation Safety Reporting System (ASRS) database. Investigating such problems in greater detail requires the capability to easily access relevant incident reports. To this end, a preliminary taxonomy of memory-related key words was developed that could be incorporated into the existing ASRS key word set. This paper provides a brief review of the methodology used to develop a memory-related taxonomy, and describes some of the lessons learned during this process that should be considered if a more comprehensive human factors taxonomy is to be developed.

BACKGROUND

The Aviation Safety Reporting System (ASRS) provides a database of incident reports that can be used for a number of purposes, including identifying deficiencies in the National Airspace System and obtaining a unique "window" into the ATC and cockpit environments that can help to guide the activities of human factors researchers. In reviewing these reports as they are received, it is not uncommon for ASRS analysts to detect problems that might merit further investigation. One such case is that of incidents that appear to involve remembering and forgetting critical flight information by pilots. The observation that such errors appear to occur sufficiently often to be a concern (Cheaney, personal communication, 1989) resulted in an ASRS project intended to address this problem.

The objective of this work was to provide a set of tools that could be applied to the investigation of types of memory problems that occur in the cockpit. Two sets of tools were developed. The first was an annotated bibliography (Mangold & Eldredge, 1991a) comprised of the cognitive literature judged to be relevant to problems of remembering and forgetting in the cockpit environment. This document provides both a stand-alone resource to other researchers and also served as a useful literature review for the preparation of the second tool, a preliminary taxonomy of key words for categorizing memory-related incident reports.

Although ASRS has served as a valuable human factors resource, an ongoing concern is the problem of accessing relevant reports. As is the case with any database, the utility of ASRS is impacted by the ease with which relevant incident reports can be accessed. Ease of access is influenced, in part, by the key words used to categorize the reports. ASRS currently has a large set of key words by which incident reports are currently coded. This key word set, however, is comprised primarily of operational terms which reflect what happened during an incident. Although a subset of these key words does reflect human factors concerns, many of the terms are too generic, such as "Complacency" and "Workload Excessive." Textual searches can be accomplished using specific words such as "remember" and "forget," but reports that do not specifically include these words in the narrative section will not be found, resulting in the occurrence of false negatives. Many researchers have found that searches are cumbersome to use in that a large number of false positives (reports that are not relevant to the researcher's interests) may be retrieved, forcing the researcher to first carefully review all of the reports obtained to sift out those which are not appropriate. Depending upon the type of search, this can be an extremely time-consuming task.

Constructing a taxonomy of human factors-oriented key words is, therefore, a tricky process. Our attempt to develop a taxonomy constrained to memory-related key words offered a useful look at some of the difficulties likely to be faced when a more comprehensive taxonomy is constructed. This paper provides a brief review of the lessons learned during this attempt to construct a limited taxonomy and suggests some of the questions that must be addressed in order to construct a more ambitious and complete taxonomy.

A CONNECTIONIST APPROACH TO THE DEVELOPMENT OF A TAXONOMY

The approach to constructing a taxonomy of memory-related key terms began with the development of a preliminary model of pilot memory. During the preparation of the annotated bibliography a set of assumptions was identified that was thought to be especially relevant to a model of memory in an applied setting, such as the cockpit environment. These assumptions clashed with many of the assumptions found in standard models of memory. Traditional conceptions of memory typically look at memory as involving the encoding, storage, and subsequent retrieval of pieces of information. According to this view, memory is a passive process that simply involves placing to-be-remembered information into the appropriate storage system and, when needed, pulling it back out in a form that differs little from the state in which it was encoded. Each piece of information is stored separately and cannot interact with any other information until it is brought out of storage.

Until recently, virtually all models of memory included some or all of the assumptions associated with the view of memory as storage bins. An alternative framework (e.g. Bransford & Franks, 1976) suggests that memory is a process. This approach argues that what we think of as the acquisition and retention of information actually involves a change in how we see and understand our world. We become sensitive to new types of information that enable us to perform tasks in ways we previously were unable to do. Memory is seen as an active capability or skill that is inherently related to all other cognitive processes, including perception, problem solving, and comprehension.

The standard model of cognitive functioning in the cognitive and human factors literature is information processing theory (see, for example, Wickens, 1984). Information processing theory builds on the storage bin concept by attempting to map the flow of information through the cognitive system. This flow involves moving information from one storage bin to another, with each bin serving as a holding area which allows the stored information to be manipulated into different forms. Because of the central role the storage bin approach plays in standard information processing theory, the assumption that memory is a process appears to be outside the scope of this theory.

During the 1980's, an alternative theory of cognitive functioning achieved recognition as an alternative to information processing theory. This theory, called *connectionism*, attempts to bring together our understanding of cognitive processes with what neuroscience has learned about brain functioning (see Smolensky, 1988, for additional details on connectionism). Connectionist models assume that cognitive processing takes place by means of networks of simple neuron-like processing units. Each unit can perform only the simplest computation, that being either to pass on or not pass on activation. The cognitive system consists of thousands of these networks. Information reaching the perceptual system causes activation to flow through the various networks. Excitatory connections between networks allow activation to flow from one network to another. Inhibitory connections are also possible, where activation of one network leads to inhibition of the connected network, decreasing the likelihood that the connected network will be activated. Connections between networks are formed in either of two ways. Some connections are formed during early brain development while others appear as a part of the learning process.

A preliminary model of pilot memory, based upon the connectionist approach, was developed to serve as a basis for deriving a taxonomy of memory terms. This pilot memory model is presented more fully in Mangold and Eldredge (1991b). The taxonomy is briefly described below.

A CANDIDATE TAXONOMY

Based upon the pilot memory model, five categories of memory-related key terms were developed. These key words are error-based in that they reflect types of breakdowns that can occur in the memory process.

Information Encoding Errors reflect the failure to adequately encode relevant information so that it can be accessed at a later time. Since totally new information is rarely learned, information encoding is assumed to involve activating and strengthening connections between the to-be-remembered (and already known) information and cues arising from the current situation that can be used, at a later time, to access the to-be-remembered information during information retrieval. For example, when the pilot is given a clearance, the task is to remember that information long enough to use it. The information itself is strictly not new, that is, the pilot already knows the various altitude clearances. What is new is the clearance within the context of the current situation. Consequently, the learning task involves relating the pre-existing information to the current situation. There is one fundamental type of information encoding error, the failure to encode relevant information. There can, however, be a variety of causes for this failure.

- Failure to encode relevant information: Wrong mental model
- Failure to encode relevant information: Network-switching lag
- Failure to encode relevant information: Nondominant network insensitivity
- Failure to encode relevant information: Distraction

Note that these causes involve combining the "failure to encode" descriptor with more specific descriptors from the other error categories described below.

Meaning Structure Errors refer to memory errors that arise because of problems with representational structures. As with other cognitive theories, the pilot model of memory assumes that mental models are formed, when performing a task, to serve as a structure for understanding the task and developing expectations as to the events that will occur as part of the task event. Mental models are activated on the basis of pre-existing connections between networks that have been built up through experience in similar situations. When a familiar situation is experienced, the relevant networks are activated and the task performer then knows how to behave in that situation. In many respects, all of the errors included in this taxonomy involve a type of mental model error in that encoding, retrieving, and attending to information all contribute to the informational content of a mental model. However, there is a set of errors that is specific to the formation of mental models having to do with activation of the wrong mental model. A number of different causes for this global error are possible, including:

- Wrong mental model: Insufficient environmental information
- Wrong mental model: Pilot induced, resulting, for example, from incorrect expectations
- Failure to complete the mental model
- Incorrect mental model formation

Processing Competition Errors refer to errors that occur when the cognitive system is busy with one task and fails to adequately manage a second task. These errors are similar to those referred to as problems of attention or workload. Memory failures can occur because the pilot was focused on one task and failed to properly encode information concerning another task or because of a lag in switching from attending to one task to attending to a second task. To avoid overloading the cognitive system of networks, inhibitory connections are used to prevent activation from flowing between unrelated networks. Focused attention is possible because of these inhibitory connections. Performing a complex task involves allowing the cognitive system to activate properly in response to information relevant for that task. Although the cognitive system can partially activate in response to a secondary task, this secondary activation is closely constrained to prevent the two activation paths from merging into one chaotic stream. However, the cognitive system can switch, making the secondary task now the primary focus. Processing Competition errors include:

- Network-switching lag, due to the time taken to shift from one activated set of networks to another
- Nondominant network insensitivity, or reduced sensitivity to non-primary task information
- Distraction, or allowing a task to become the primary task when it should not be

Information Retrieval Errors reflect the failure to achieve the same cognitive state at information retrieval as was present when the information was encoded. Retrieval is assumed to be a form of reactivation. The goal is to reinstate the same cognitive state, that is, network activation pattern, as was present when that information was initially encoded. This reinstatement process is guided by a range of cues, including the context in which the information was encoded, other information that was encoded at the same time (or is similar to the to-be-remembered information), and any other cues that will activate the same perceptual and cognitive paths that were active during encoding. The combination of these cues is usually sufficient to access the to-be-retrieved information. Retrieval failures can occur, however, if the retrieval environment differs from the encoding environment or if the to-be-retrieved information is similar to other information, thus causing interference to occur. Consequently, the two types of Information Retrieval errors are:

- Interference due to similar information
- Dissimilar retrieval context or cues, that is, dissimilar from the original learning context

Artifact-Induced Errors arise because of the unique demands of the advanced automation cockpit. An important role of automation should be to compensate for cognitive limitations of the flight crew. For example, the flight management system (FMS) can be programmed to provide long-term control of the aircraft. The pilot programs the flight plan into the FMS, then turns control of the aircraft over to the FMS, acting only as a monitor of the aircraft's performance. One common type of memory error is to forget to adequately monitor the aircraft. The pilot's attention may be focused appropriately on the aircraft and the system when the change is initiated, but all too often, the pilot may forget to check on the system at a later time. During that interval, numerous events can occur that distract or otherwise occupy the pilot, making it very difficult to re-focus back on the original task in a timely manner.

APPLICATION OF THE TAXONOMY TO INCIDENT REPORTS

Once a taxonomy of key words has been identified, the next step is to apply this taxonomy to actual incident reports. The taxonomy must support consistent application of the key words to the reports by analysts, which means there must be an objective procedure for determining when a key word applies to a given report. The guiding procedure in the current work for ensuring that key words can be consistently applied is the identification of relevant situational factors. Situational factors refer to certain conditions, mentioned in the original report, that suggest some of the factors which may have contributed to the occurrence of the incident. In a complete taxonomy, key word definitions would include a list of contributory conditions, at least some of which must exist in order for a key word to be applicable to a report. A number of examples of how situational factors guide the application of terms to incident reports are provided in the original report (Mangold & Eldredge, 1991b). Because of space limitations only one such application is provided here.

The incident involved a failure of the flight crew to achieve the required altitude. During climbout the crew was given an altitude clearance. The captain acknowledged and entered 11,000 feet in the altitude alert window. Only after reaching this altitude did the crew realize that the actual clearance was to level off at 10,000 feet. The captain suggested several reasons (situational factors) for the confusion:

- Climbout is a high workload phase of flight.
- The ATC clearance was complex, involving several components in addition to altitude.
- The call sign for the flight was "11XY."
- Common clearances during climbout are 10,000 or 11,000 feet.
- When he is the pilot flying, the captain noted that he frequently misses the initial radio call altitude assignment.

Based upon the occurrence of these factors, three memory-related key words should be assigned to this report. First is *information overload* because of the busy nature of the phase of flight and because of the complexity of the clearance. Second is *interference due to similar information*, in response to the apparent confusion between the clearance and the call sign. Finally, there was *nondominant network sensitivity* by the captain. When focused on the visual task of flying the airplane, there may have been a reduction in the sensitivity of other modalities, such as audition. This may have resulted in missing the first part of a radio transmission.

Note that these situational factors are contributory but no claim is made that these factors did cause the memory failure. However, the occurrence of these situational factors does offer some possible reasons for why the incident took place. These reasons are then described by means of the key words associated with those factors.

LIMITATIONS OF THE CURRENT APPROACH

The work described here is clearly preliminary in nature and does not claim to provide a complete and justified set of key words. Given this caveat, there are, nonetheless, potentially more serious problems with this work, which were raised by a reviewer of the original report (Dismukes, December, 1992). Dismukes had a number of reservations with this work, the primary concern being the arbitrary nature of the key words. This criticism has two sources: (1) It may be possible to derive the same key words from a theoretical framework other than a connectionist type of model. (2) It is possible that a different set of key words could be obtained from the same model.

Both criticisms have some validity, but it is not clear that Dismukes' concerns are fatal to the approach used here. One solution Dismukes proposes for resolving the problem of an arbitrary taxonomy is to work towards explicitly modeling cognitive aspects of pilot behavior that can then be experimentally verified or falsified. The resulting set of models would then serve as the foundation for a taxonomy of key words. However, these models do not yet exist at the level of specificity that is required, and it is not clear that the human factors community is even close to providing such models (see, for example, Elkind et al., 1990). Should the development of a taxonomy be deferred indefinitely until these models are available?

It is also not clear that these models are essential to the process of developing a taxonomy. The ultimate objective of a taxonomy is not to provide a comprehensive understanding of pilot functioning but rather to serve as a tool for accessing relevant incident reports. Given this objective, the question then is what criteria define a usable taxonomy. Some candidate criteria for a taxonomy are that it:

- refer to unique and important cognitive phenomena
- can be applied consistently to a set of reports by different analysts
- can be easily translated into the terminology of other cognitive theories.

The pilot memory model was developed simply to serve as a means to an end, the end being the development of a usable taxonomy. It is quite possible that other theoretical frameworks could be used. The pilot memory model did serve the primary purpose of forcing clarification of how memory is to be viewed. A storage bin view of memory will result in a different set of key words because the characteristics of memory and the ways in which memory is assumed to fail differ from a process model. Perhaps specification of a particular model is less important than specification of the assumptions used to conceptualize memory and forgetting. However, provision of a clearly specified model of pilot memory, even if it is known to be incorrect, may serve the important role of providing the human factors researcher with a means of better understanding how the various forms of memory and forgetting have been defined.

Dismukes also raised the important concern that this type of taxonomy would not be usable by an analyst. ASRS analysts are experienced former pilots and air traffic controllers. Although they possess an extensive background in operations-oriented issues, it is unlikely that they will also have a strong background in human factors research and theory. Any taxonomy that cannot be efficiently and consistently used by the analysts has no value. Resolution of this difficulty may lie in the role played by the situational factors. If the individual taxonomic elements are clearly and unambiguously tied to specific situational factors, it should be possible for the analysts to consistently and correctly assign key words to incident reports. This is, of course, a potentially big "if."

The third criterion for a usable taxonomy, that it be easily translated into the terminology of other cognitive theories, may be more easily satisfied if the researcher has a strawman memory model which can then be used to more readily understand the specific ways in which key words are used. Provision of such a model could enable researchers to use it as a way of understanding the meanings of the key words so they can then determine how to map their own theoretical terms onto the taxonomy and more effectively choose the appropriate set of key words to guide their search.

WORK TO BE ACCOMPLISHED

Any human factors taxonomy will have to carefully balance two somewhat different sets of needs. The analyst needs a clearly defined, manageable set of terms that can be easily matched to the appropriate incident reports. The taxonomy should be small in number to avoid substantial memory and time demands on the part of the analyst. On the other hand, the taxonomy must meet the somewhat different needs of the human factors researcher who requires that the taxonomy encompass a breadth of topics and differentiate these topics in a meaningful way. While a small taxonomy is probably helpful to the analyst, a larger taxonomy may be more useful for the researcher so as to minimize the number of false positive reports.

To satisfy both sets of needs, the work performed to date must be supplemented in several ways. First, the set of key words needs to be compared with the cognitive literature to ensure that it possesses the scope to encompass the range of memory and forgetting phenomena addressed in the literature. In addition, the key words need to be reviewed by others to ensure that their meaning is clear. This process includes a clearer specification of the situational factors associated with each key word. Finally, it may be useful to look at candidate tools that might be used for organizing the key words in a way that will aid the analyst. One possibility is to enable the analyst to use the situational factors described in the report to then access the candidate key words. In this way, the analyst's strong understanding of the contributing situational factors could be used to advantage and reduce the difficulty in selecting the appropriate key words.

There are additional, unsolved problems unrelated to taxonomic definition that will, nonetheless, impact the ultimate usability of a taxonomy. Key among these is the problem of incomplete information in the original report. If the reporter does not mention critical situational factors, assignment of accurate key words is clearly impacted. Methods for obtaining more complete human factors information will eventually need to be addressed.

REFERENCES

Bransford, J. D., & Franks, J. J. (1976). Towards a framework for understanding learning. In G. H. Bower (Ed.), *The psychology of learning and motivation (Vol. 10).* New York: Academic Press.

Elkind, J. I., Card, S. K., Hochberg, J., & Huey, B. M. (1990). *Human performance models for computer-aided engineering.* Boston: Academic Press.

Mangold, S. J., & Eldredge, D. (1991a). *Literature relating to pilot cognition and memory processes.* NASA Contractor Report, publication pending.

Mangold, S. J., & Eldredge, D. (1991b). *An approach to modeling pilot memory and developing a taxonomy of memory errors.* NASA Contractor Report, publication pending.

Smolensky, P. (1988). On the proper treatment of connectionism. *The Behavioral and Brain Sciences*, **11,** 1-23.

Wickens, C. D. (1984). *Engineering psychology and human performance.* Glenview, IL: Scott, Foresman.