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relate to previously encountered details. The expert programmer will be able to retrieve these details by scrolling back through the listing to their location. Retrieval is accurate even when the number of such details exceeds working storage capacity. According to Altmann, this is because each time a detail is encountered, the programmer attempts to understand it by using their expert knowledge of programming. This produces an 'event chunk' specifying the episodic properties of the detail (e.g. its location in the listing), which are retained in near-term memory. Thus near-term memory provides a link between external information and expert semantic knowledge, with the result that key details can be retrieved when needed.

Recent research has attempted to find ways to reduce the 'cognitive burden' on software engineers. This has included designing artificial cognitive systems to support human software developers by carrying out some of the cognitive functions currently undertaken by human programmers (Chentouf, 2014).

5.5 WORKING MEMORY IN AIR TRAFFIC CONTROL

THE ROLE OF WORKING MEMORY IN THE AIR TRAFFIC CONTROL (ATC) TASK

The volume of air traffic has increased dramatically in recent years, and it is likely to increase further as air travel grows; if future demand is to be met safely, our understanding of the mental workload of the air traffic controller will need to improve (Loft *et al.*, 2007). Several studies have identified working memory as playing a role in the performance of the ATC task (Smieszek *et al.*, 2013). ATC is a complex and demanding safety-critical task and the air traffic controller deals with transient information to which a number of executive control processes must be applied. This information must be retained and updated in working storage for tactical use or strategic planning along with related outputs; as a result, performance of the ATC task is constrained by working memory limitations (Smieszek *et al.*, 2013; Garland *et al.*, 1999; Stein and Garland, 1993).

Working memory allows the controller to retain and integrate perceptual input (from the radar screen, flight strips and audio communications) while simultaneously processing that information to arrive at tactical and strategic decisions. Tactical information retained in working memory includes aircraft altitudes, airspeeds, headings, callsigns, aircraft models, weather information, runway conditions, the current air traffic situation and immediate and potential aircraft conflicts (Stein and Garland, 1993).

Figure 5.5 Air traffic controllers.
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And since the air traffic situation is constantly changing, the contents of working memory must be constantly updated.

An overarching requirement of the en-route ATC task is to maintain 'separation' between aircraft (usually a minimum of 5 nautical miles horizontally). The controller must anticipate and avoid situations that result in a loss of separation (aircraft 'conflicts' or more generally 'operational errors'). The dynamic nature of the air traffic environment ensures that this requires the execution of a number of control processes within working memory. One such control process involves the scheduling of actions. For example, a controller may instruct several aircraft within their sector to alter altitude or heading. It is imperative that these manoeuvres are carried out in an order that avoids the creation of conflicts between aircraft. In addition, scheduling must be responsive to unanticipated changes in the air traffic environment, which may require schedules to be updated (see Niessen *et al.*, 1998; Niessen *et al.*, 1999).

Dynamic scheduling of this sort is an important function of working memory (Engle *et al.*, 1999). Another executive function of working memory is the capacity to process one stream of information while inhibiting others (Baddeley, 1996). Such selective processing is an important feature of the ATC task. For example, controllers reduce the general cognitive load of the task by focusing their attention on prioritised 'focal' aircraft (which signal potential conflicts) and temporarily ignore 'extra-focal' aircraft (Niessen *et al.*, 1999). Moreover, dynamic prioritisation is itself an important control process in ATC that requires flexible executive resources.

It is worth noting that the flexible use of attentional resources is also regarded as key in many other dynamic tasks, including those relating to pilot cognition. Wickens and Alexander (2009) use the term 'attentional tunnelling' to describe the 'allocation of attention to a particular channel of information, diagnostic hypothesis, or task goal, for a duration that is longer than optimal'. Wickens and Alexander provide the example of Eastern Airlines flight L1011 which crashed in the Florida Everglades. While focusing attention on what appeared to be a landing gear malfunction, the pilots failed to attend to their descending altitude, with tragic consequences. Similarly, many road traffic accidents in which drivers are speaking on mobile phones may involve attentional tunnelling on their conversations at the expense of attending to the driving task. It is possible that attentional tunnelling is also responsible for some of the operational errors in ATC, particularly under conditions of stress when 'attentional narrowing' may be present.

Clearly, ATC requires controllers to make use of a great deal of knowledge stored in long-term memory. During training, controllers acquire declarative and procedural knowledge without which they would be unable to perform the ATC task. Indeed, in ATC, working memory is dependent upon long-term memory for a number of key cognitive operations, including the organisation of information, decision making and planning (Stein and Garland, 1993). The temporary activation, maintenance and retrieval of information in long-term memory are processes controlled by the central executive component of working memory (Baddeley, 1996). Thus, working memory plays a key role in the utilisation of the long-term knowledge used to interpret and analyse information emanating from the air traffic environment.

The avoidance of air traffic conflicts is essentially a problem-solving task and problem resolution is a key information-processing cycle in ATC (Niessen *et al.*, 1999). Working memory plays an important role in problem solving by retaining the initial problem information, intermediate solutions and goal states (Atwood and Polson, 1976). The working storage of goals and subgoals appears to be essential in a wide range of problem-solving tasks. Indeed, when the rehearsal of subgoals is interfered with, both errors and solution times increase (Altmann and Trafton, 1999). In ATC, goal management is a dynamic process because goal and subgoal priorities change as a function of changes in the air traffic environment. In executing a plan to attain a goal, the controller may need to retain in working storage a record of the steps currently completed and those that remain to be completed. Each time a step is completed, the contents of working memory need to be updated to record this fact.

Goals and subgoals can also change before they are attained. For example, changes in the air traffic situation can result in the removal or creation of goals and produce changes in the priority of existing goals. The management of goals is another important functional aspect of working memory and empirical studies have shown that when additional working memory resources are made available to goal management, problem-solving performance improves (e.g. Zhang and Norman, 1994).

SITUATION AWARENESS

The dynamic nature of the air traffic environment means that controllers must have an accurate awareness of the current and developing situation (Wickens, 2000). In this context the term 'situation awareness' refers to the present and future air traffic situation, and a number of studies have identified situation awareness as key to safe and efficient air traffic control (e.g. Endsley, 1997; Niessen *et al.*, 1999). Experienced air traffic controllers often describe their mental model of the air traffic situation as the 'picture' (Whitfield and Jackson, 1982). The picture contains information about the fixed properties of the task and the task environment (e.g. operational standards, sector boundaries, procedural knowledge) as well as its dynamic properties (e.g. current and future spatial and temporal relations between aircraft). Thus, although some of the content of the picture is retrieved from long-term memory, working memory is involved in the retention of the assembled picture (Logie, 1993; Mogford, 1997). Moreover, the variable nature of the air traffic environment means that the picture needs to be repeatedly updated using executive control processes in working memory.

Endsley (1997) sought to identify and examine the psychological factors responsible for operational errors in en-route air traffic control. A total of twenty-five duty controllers observed re-creations of operational errors and reported on their situation awareness and cognitive workload. The results showed that under conditions of high subjective workload, situation awareness was compromised as attention was allocated to prioritised information. Endsley reports that under high workload, controllers had significant deficiencies in ongoing situation awareness, with low ability to report the presence of many aircraft, their locations or their parameters. When a high number of aircraft were present, controllers prioritised situation awareness of aircraft separation at the expense of other aspects of the situation.

These findings can be better understood by considering studies that have identified the detailed nature of situation awareness in ATC. Using a sample of experienced en-route controllers, Niessen *et al.* (1998, 1999) identified a number of 'working memory elements' (WMEs) that comprise the 'picture' used in ATC. They found that the picture consists of three classes of WMEs: *objects*, *events* and *control elements*. Examples of object WMEs are incoming aircraft, aircraft changing flight level and proximal aircraft. Events include potential conflicts of a chain or crossing kind. Control elements include selecting various sources of data (e.g. audio communication, flight level change tests, proximity tests), anticipation, conflict resolution, planning and action. Control procedures select the most important and urgent WMEs, which are arranged in working memory in terms of their priority. The continuously changing air traffic environment requires that 'goal-stacking' within working memory is a flexible process.

VOICE COMMUNICATION

Clearly voice communication with pilots and other controllers is an important element of the air traffic control task. Via radio, the controller may convey instructions to pilots and receive voice communications from pilots. Voice communication errors can contribute to serious aviation incidents (Fowler, 1980). A tragic example is the collision between two 747s on the runway of Tenerife airport in 1977, which resulted in the deaths of 538 people and which was partly the result of a voice communication error (Wickens, 2000). Misunderstandings account for a substantial number of voice communication errors and many of these result from overloading working memory capacity (Morrow *et al.*, 1993). Working memory assists speech comprehension by retaining the initial words of a sentence across the intervening words, thereby allowing syntactic and semantic analysis to be applied to the complete sentence (Baddeley and Wilson, 1988; Clark and Clarke, 1977).

'b' 'c' 'd' 'e' 'g' 'p' 't' 'v'

BDP4, TCG4, CEG4, VTP4

Figure 5.6 Examples of phonologically confusable letters and call-signs.

In addition to comprehension failures, voice communication errors can also result from confusions between phonologically similar items in working memory. For example, the call-signs BDP4 and TCG4 contain phonologically confusable characters, increasing the risk of errors relative to phonologically distinct equivalents (Logie, 1993) producing a 'phonological similarity effect' (see Figure 5.6).