Expertise in Aviation

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Introduction

In 2009, Captain Chelsey "Sully" Sullenberg landed a crippled aircraft, loaded with 150 passengers and no power following a bird strike, on the Hudson River in New York. The incredible skill shown by Captain Sullenberg and his co-pilot Jeffrey Skyles was credited with saving the lives of all on board in what could have been a near total disaster. Other examples of skilled piloting saving lives abound, including the landing of another totally crippled airline with no steering capability on the runway at Sioux Falls Iowa. Here, because the runway surface is far less forgiving than a river surface, many lives were lost; but equally many were saved. Again, the incredible skill and expertise of the pilot, Captain Hanes, and his crew were credited for this disaster management.

These two disaster management responses reveal many different aspects of aviation expertise. Certainly, the finely tuned stick and rudder flying skills of Captain Sullenberg, reflecting his perceptual-motor coordination skill, permitted him to maintain a dangerously unstable aircraft on its critical glide slope to hit the water at precisely the correct angle and at high speed, so that its nose or wings did not penetrate the water and invite a catastrophic upset. For Captain Hanes, his calm communications skills, ability to harness all the resources of both his cabin crew, an extra skilled pilot on board, and the services of air traffic control were all critical in accomplishing the life-saving actions. These factors combine as a set of skills known as crew resource management, which were first documented in the social psychology literature (Foushee, 1984; Salas, 2010). In between these skills supporting two disparate research areas in applied psychology (i.e., perceptual-motor coordination and social psychology), lies the expert decision making skills of pilots, exhibited in the examples above in the choice of how and where to land.

In this chapter, we will describe the nature of expertise in aviation, both on the flight deck and also in air traffic control (we here define both as *aviation professional*). We investigate what changes occur in these professionals with learning, and how an expert differs from a novice. In doing so, we first define what we mean by *expertise* in aviation, considering two alternative approaches: the amount of flight experience and the level of proficiency. Next, we provide a clear description of the different psychological skills required of the aviation professional and their relationship to more fundamental information processing abilities. Then we review the research that has distinguished between levels of proficiency, typically novice from expert aviation professionals, or has evaluated the change in skill differences as learning takes place. Finally, we briefly describe research that has tried to adopt novel training strategies to accelerate the trajectory of skill development.

Defining Expertise

There is an important distinction between the two different ways in which expertise has been defined in aviation. On the one hand, it is easy to define expertise a-priori, in terms of the amount of flight experience. This is typically characterized by the total number of hours spent piloting an aircraft (henceforth, flight hours). In some cases, the number of flight hours in visual flight (i.e., when the ground is in sight, (visual meteorological conditions or VMC) is differentiated from those spent in instrument flight conditions (Instrument meteorological conditions or IMC; i.e., when it is not and the pilot must rely totally on navigational instruments). These two conditions are the basis for two types of pilot ratings or certifications. With only a visual flight rating (or VFR), the pilot cannot fly in IMC (Instrument Meteorological Condition). With an instrument flight rating, (IFR), the pilot can fly in both VMC and IMC, and is considered more proficient. Finally, sometimes, experience is also defined in terms of flight qualifications. In particular, those qualified to fly only general aviation are considered less proficient than those also certified to fly commercial transport aircraft, as run by the airline industry.

The second distinction of aviation professional expertise, is simply how *proficient* the professional is at his or her task. Although we could credit the proficient management of individual incidents (such as those described at the outset), as being representative of an expert level of proficiency, we cannot necessarily say that this was a consequence of their many hours of both instrument and visual flight, nor whether these efforts would be repeatable and, therefore, truly expert. Indeed, National Transportation and Safety Board accident reports are replete with similar examples but of tragic accidents, attributable to the errors of pilots who had many years of experience, such as the crash of an Eastern Airlines Jet into the Everglades (Wiener, 1977; Dismukes Berman & Nowinski, 2011). As is true in many other domains, years of experience does not guarantee a high level of proficiency (Ericsson & Charness, 1997), particularly with a skill as critically dependent on fluent decision making as is the case with aviation. As has been previously noted, decision making is a task that is often ill suited for learning from experience (Einhorn & Hogarth, 1978).

Aviation Tasks

The Pilot's Tasks.

Conventionally, the work of a pilot has been categorized into four tasks considered primary:

1. Aviate. This is the standard perceptual-motor *stick and rudder* task required to keep the plane airborne. It involves selecting the right combination of *airspeed* via the throttle, *pitch* (nose pointed upward or downward) via controls on the wings and the elevator on the tail, and *bank angle* via the ailerons located on the wings so that the air flow is greater over the wings than beneath them. This differential flow in turn creates a partial vacuum above the wings, which literally *lifts* the aircraft upward toward the sky. There is greater lift when the aircraft if flying faster through the air, and when the wings are level. When this lift is lost, the plane will *stall* and start to fall toward the earth. In addition to maintaining lift (and preventing stall), these controls with the stick and throttle serve to change the aircraft's *attitude* (bank and pitch) in a way that can direct it to different vectors or *3D trajectories* through the air (e.g., turn, climb, descend, accelerate or decelerate). These changes in turn are the basic building blocks of navigation as described below.

What makes aviating so complex, and requires a great amount of skill development is the fact that all of these axes are cross-coupled (i.e., each action has both primary and secondary effects). For example, when a pilot banks to turn the plane, it can also start to *slide* downward, hence both losing altitude and gaining airspeed. And when the pilot pitches the airplane upward to climb, it will also lose airspeed. Such cross coupling of primary and secondary effects requires a great deal of mental integration. Also, with larger aircraft, there is a greater lag between when a control is implemented, and when the plane starts to change the controlled variable. The dynamics of manual control systems are such that dealing with lags requires mental prediction which is cognitively quite demanding (Wickens & Gopher, 1977; Wickens, 1986; 2003; 2007). Failure to aviate well is often a precursor to a *loss of control* (LOC) accident--the most lethal kind of accident in both commercial and general aviation. Failure to properly aviate has been identified as the causal factor for half the accidents of general aviation pilots in the UK during a 6-year period (Taylor, 2014).

2. Navigate. While, aviating can put the plane on a trajectory to establish where is it going, navigating determines the precise trajectory (e.g., a climb to 5000 feet, a heading of 270 degrees) and precise targets (e.g., a fix over a certain point on the ground, at a particular altitude, at a point in particular time). Airborne navigation can be particularly challenging because of the number of attributes to be controlled (heading, climb, altitude, position, speed in four dimensions), and targets may be specified in various frames of reference (Wickens, 1999; Wickens Vincow & Yeh, 2005). For example, a navigational command may be given in a world-referenced frame (fly 250 degrees), but exercising it may require thinking in ego-referenced terms (I must turn 40 degrees from my current heading). The cognitive demands of transforming between different frames of reference (mental rotation) are familiar any time we are driving southward, negotiating complex intersections, while consulting a north-up map (Aretz & Wickens, 1992; Wickens, 1999; Wickens et al., 2005). These complexities are amplified in 3 dimensions.

The close relationship between aviating and navigating has been described as a form of mental calculus—every bit as challenging as learning to intuitively apply integral and differential calculus computations(!!)—because the parameters controlled in aviating are generally integrated over time to establish the navigational goals (Wickens, 2007). One should note that both of these tasks (aviate and navigate) are, in many aircraft, supported by various forms of automation and technology. Autopilots can relieve the pilot of many aspects of aviating. Likewise, new navigational systems and some advanced displays can alleviate many of the mental transformations of navigating. However, such systems are always susceptible to failure, and it seems reasonable to assume that pilot skills at flying the aircraft *by hand* should always be practiced. Also training a pilot to fly should always proceed through the sequence of hand flying, before learning the capabilities of automation.

3. Communications. This refers primarily to voice communications between the pilot and air traffic control (Mosier et al., 2013). Verbal *protocols*—precise *readback* of controller's instructions and precise *hearbacks* by the controller (who must assure that the pilot reads back precisely what the controller said)—must be maintained during their communications. This activity also requires tuning of the radios to different frequency channels, in order to deal with different controllers along the flight path. The challenge of precise communications is amplified by two factors. First, so much of it is accomplished by voice, and the auditory modality which is so susceptible to short term memory forgetting (Latorella, 1996, Helleberg & Wickens, 2003, Gateau, Durantin, Lancelot, Scannella & Dehais, 2015, Gateau, Ayaz, Dehais, 2018). Second, much of it involves numbers, which, if confused, can have catastrophic consequences (e.g., confusing or mis-remembering a heading, altitude and airspeed command of 320, 25, 350 respectively, as, for example, 350, 25, 320).

***4. Systems management**.* This refers to assuring the proper mechanical and electrical status of all on board systems, such as power, fuel, engine functioning, as well as assuring the correct functioning of navigation and aviating systems. Systems management primarily involves monitoring and awareness the system status, whereas the prior three tasks also require the performance of specific, and often skilled, actions. However, system management can also escalate rapidly into required diagnosis, which involve action-driven trouble-shooting and systems corrections when things go wrong.

***5. Mission tasks**.* In addition to the above primary tasks, many flights also require a *mission* oriented task. An aerial photographer must photograph, a fire tanker must drop its load of fire retardant precisely, and of course almost all military aircraft have a mission-critical combat objective. These are often added to the four requirements of basic flying.

***Task hierarchy**.* The four primary tasks of **A**viate, **N**avigate, **C**ommunicate, and **S**ystems management (ANCS) are listed in the above order because it is generally considered that these tasks are hierarchical and pilots should adhere to this ordering of prioritization when tasks conflict. For instance, unless the pilot keeps the plane in the sky (aviate), he or she cannot accomplish any of the tasks below it in the hierarchy; and, for safety reasons, the pilot should always know where the plane is travelling and where it is, regarding navigational goals and hazard avoidance, before engaging in communication or systems management. The ANCS hierarchy needs to be flexible because certain tasks may temporarily demand top priority (Schutte & Trujillo; 1996). These task management skills, referred to as cockpit task management (CTM; Funk, 1991), are in themselves complicated and constitute important features of expert piloting. We discuss these features of expert piloting below in the sections on *Task Management* and *Expertise in Aviation*. Next we discuss the tasks in which expert air traffic controllers engage.

Air Traffic Controller Tasks.

The controller can have a work environment that is in many ways every bit as demanding as that of the pilot; even as it contains only two, rather than five major task categories (Wickens, Mavor, & McGee, 1997). These tasks can be defined as:

Maintaining separation. The number one safety priority of the controller is to keep planes from colliding, in the air, or on the airport surface. To ensure that this is the case requires that the controller keeps each aircraft outside of a *protected zone* around each other one, a sort of cylindrical *hockey puck* of a designated vertical and circular extent (this may vary in its size, depending on the region of the airspace). To accomplish this, controllers are required to have an extensive amount of 3D visualization skills, particularly those involving spatial prediction. If one plane is flying toward another's protected zone, a command issued to the pilot to avoid penetration must be issued well before the zone is penetrated. And such proactive control requires the skill of making predictions (Boudes & Cellier, 2000).

Maintaining flow. An individual plane does not require controllers to direct it from start to destination. However, in the commercial airspace it is necessary that controllers maintain the collective flow between airports. This means they must continually control departures and arrivals. The controllers maximize the efficiency of travel, and hence minimize delays by managing the fundamental components of navigation (speed, heading, and altitude) of an entire stream of aircraft.

Efficiency goals, such as *maintaining flow* of air traffic, and safety goals, such as *maintaining separation* between aircraft are somewhat conflicting. In a busy airspace, efficiency can be preserved only by tightly packing planes together. This can occur only up to a limit where separation standards are not violated. But where that boundary is difficult to establish, the balance between these competing forces is a key characteristic of controller proficiency. Unlike the pilot's clear definition of a task hierarchy, the relative priority for maintaining wide separation versus flow, is not as easily determined given its conflicting nature.

Communications. Communications is a task shared equally by pilots and controllers. Although it may be argued that since the controller is generally in charge of issuing voice instructions, comprehension skill demonstrated during this exchange is most vital for the pilot, who after all is doing the majority of listening.

As in other societal-technical domains of high complexity such as medicine or power plant management, so the skills in aviation may be divided into the so-called "technical skills", related specifically to the task of controlling the aircraft, and non-technical skills of a more generic nature.

Cognitive or Non-Technical Skills.

At a slightly different level of description from the aviation task-oriented skills above that are clearly articulated in pilot and controller training manuals are a set of what we define as cognitive, or *non-technical skills* that can often differentiate better from poorer performing aviation professionals. We discuss four of these fundamental skills as follows.

Task management. We referred briefly to task management skills above in the context of the ANCS priority hierarchy on the flight deck of cockpit task management (Chao, Madhavan, & Funk, 1996). But good task management skills go beyond adhering to this hierarchy to include such skills as:

- Effectively & flexibly moving a lower hierarchy task toward the top in case of an emergency (Schutte & Trujillo, 1996). For example, an engine overheat may suddenly bring systems management to a greater priority than navigating.

- Switching with sufficient frequency between tasks to avoid some form of cognitive tunneling on a task deemed high priority (e.g., troubleshooting an engine failure), at the expense of other safety critical tasks (e.g., altitude or airspeed monitoring; Wickens & Alexander, 2009)
- Resisting dealing with a low priority interruption while in the middle of performing a higher priority task (Latorella, 1996).
- Remembering to return to a temporarily deferred task (Loukopolis, Dismukes, & Barshi, 2009).

Failures of appropriate task management in any of the four types above have been attributed as the cause of aircraft and ATC mishaps (Loukopolous, Dismukes, & Barshi, 2009; Dismukes, Berman, & Nowinski & 2010; Wickens, 2003). We examine below the extent to which these improve with expertise.

Decision making and diagnostic skills. Since the pioneering work of Jensen (1982) and Wiener (1977), aviation professionals have realized the vulnerability of pilot and controller performance to making inappropriate or non-optimal decisions and judgments that lead to accidents. For every good decision in crisis, such as that made by Captain Sullenberger to try to land on the river, there are countless poor decisions. These include examples such as the decision of a pilot who is not instrument rated, to try to *fly through* bad weather (Wiggins &

O'Hare, 1995) in order to reach a final destination at all costs. A study conducted by the French Safety Board revealed that such erroneous behavior (*perseveration*) was responsible for more than 40% fatalities in general aviation (see Dehais, Tessier, Christophe, & Reuzeau, 2010). This trend to persist in hazardous decision making also occurs in commercial aviation (Dehais et al., 2019). For instance, 97% of all unstabilized approaches end up with a decision to land (Curtis & Smith, 2013). These typically lead to satisfactory outcomes (potentially via good luck), but are occasionally the source of tragic fatalities, such as the decision by a pilot to take off with ice remaining on the wings at Washington National Airport in 1987 (see Helmreich, 1997).

The study of cognition, and decision making in particular, have provided a great deal of knowledge on how decision skills are learned (e.g., for reviews, see Hoffman, Ward, Feltovich, DiBello, Fiore, & Andrews, 2014; Suss & Ward, 2015) and it is often assumed that such skills will naturally develop with *time on task* or years of flight experience. Yet certain specific characteristics that we discuss below render the acquisition of skilled pilot judgment a slow and sometimes unreliable process.

Situation awareness. Numerous aviation accidents have been directly attributed to a loss of situation awareness (SA), where a pilot or controller fails to maintain the big picture of what is going on, fails to notice changes in the environment or to predict the implications of the evolving situation (Jones &

Endsley, 1996; Durso & Alexander,2010, Hopkin, 1999; Wickens, 2002). SA (or its complement, the Loss of SA: LSA), can apply to almost any dynamic feature of the aerospace environment, including the awareness of:

- Aircraft attitude (pitch and roll)
- Navigational and geographical information
- Personnel (e.g., "what is my captain doing/thinking?").
- System and automation state.

Orthogonal to these four examples of dynamic processes to be aware of, lie three components or *levels* of SA (Endsley, 1995, 1999).

1. *Noticing* that things have changed, a process heavily dependent on visual scanning (level 1 SA).
2. *Understanding* the meaning of changes, a process heavily dependent on prior knowledge (level 2 SA).
3. *Predicting* the implications of the change, a cognitive activity quite dependent on working memory, a process dependent upon both prior knowledge and working memory (level 3 SA).

While these categories map onto the pilots' task hierarchy, the skill of maintaining SA is thought to be more general than the particular knowledge and skill set associated with any one of the ANCS tasks. Effort has been invested in trying to assess and train SA skills that might benefit any and all of the above tasks.

Crew resource management. Some skills emerge uniquely in a team, whether between pilot and co-pilot on the flight deck, or between flight deck personnel and ATC or the cabin crew. These have been termed Crew resource management, which include communications skills. However, these go well beyond adhering to the strict communications protocols described above, to include effective communications in emergencies where there may be no protocol, and harnessing of effective teamwork strategies, including what has been described as team situation awareness (Stanton, 2018). As with the other non-technical skills described above, airspace incidents and accidents provide plentiful examples where CRM was both effective in *saving the day* (e.g., the Sioux City crash), or was found wanting, leading to confusion, uncertainty and, often disaster (e.g., the crash of a commercial airliner in the Florida Everglades, when all three personnel on the flight deck concentrated on a potential landing gear failure, and did not pay attention to alitude) (see O'Hare & Roscoe, 1993).

Expertise in Aviation

Taken together, both technical and non-technical skills define a powerful array, which should differentiate the expert and highly experienced pilot or controller from one who either has little experience or performs poorly at the task. But is this intuition correct? Below we review the experimental and descriptive data for the different categories of skills that indicate the extent to which these intuitions are correct, and the more specific features that differentiate levels of expertise. To the extent that these skills do differentiate across levels of proficiency, we examine the success of training strategies targeted directly at the four non-technical skills, to establish if the trajectory of expertise can be shortened.

In the following section we review the literature on professional aviation expertise. Our operational definition of expertise is high proficiency in performing aviation tasks. As such, proficiency may be assessed by instructor ratings, objective quality of performance on subtasks or often, as is the case particularly of pilot judgment, of decision outcomes that are either labeled *good* (e.g., turning back in deteriorating weather) or *poor* (e.g., flying on into a storm). At the extreme, mishaps and accidents are often the consequence of poor performance. Increasing *expertise* implies better outcomes, and the *expert* is one who consistently produces the best outcomes.

Our review seeks to understand three main factors that may contribute to outcome quality:

- Flight or ATC *experience* and certification or type ratings
- Natural cognitive or psychomotor *abilities.* These may sometimes extend to personality types or measures of cognitive style.
- Certain *cognitive strategies* that are typically learned through aviation experience. Prominent among these which we will discuss are ocular-motor or visual scanning strategies.

The four main non-technical skills described above often mediate the relationship between the three main intervening variables and the outcome For example, an aviator may demonstrate good outcomes because she possesses superior situation awareness **Trapsilawati., Wickens, Cheun & Qu, X. (2017)** However we note that in many cases these non-technical skills represent the final outcome of aviation performance assessment. Finally, we consider two phenomena well known to develop with experience, whether through deliberate practice or simply on-the-job training (e.g., Patrick, 2006), the decreased attention demands of performance, known to occur with a phenomenon termed *automaticity* (e.g., Fisk Ackerman & Schneider, 1987), or an increase in knowledge (e.g., Simon & Gilmartin 1973). We refer to these two phenomena as the *known signatures of expertise*.

The Research

In the following pages we first discuss research supporting two of the most prominent features of expertise in general, automaticity and knowledge. We then consider the findings of general changes in performance that result as expertise develops before considering in depth, how these are expressed in the non-technical skills of improved situation awareness, better decision making and improved task management and resource management skills. A final research section is devoted to explicit efforts to train these non-technical skills.

Known Signatures of Expertise

Automaticity and spare capacity. It has been long known that increasing practice on a task, whether deliberate, or just through repeated performance reduces the attention/resource demands of the task (Fitts & Posner, 1967). This is one feature of a characteristic we refer to as automaticity (Fisk Ackerman & Schneider, 1987; Schneider & Shiffrin, 1977). One consequence of automaticity is to make available attentional capacity for use on other tasks, which often results in improved time sharing. This phenomenon was well illustrated by Damos (1978) who demonstrated that flight instructors with greater flying experience performed better on a secondary task performance while flying than of student pilots (novices).

There is also some evidence that individual differences in cognitive ability can play a role in making available spare attentional resources. In particular working memory (WM) span needed, for instance, in flight communications has been shown to vary broadly across people in general (e.g., Engle, 2002) and pilots specifically (e.g., Morrow et al, 2003). Hence those with greater WM span should demonstrate greater proficiency on other tasks while engaged in tasks that place a considerable demand on working memory.

It is important to note however that individuals develop automaticity better on some tasks or, more specifically, some individuals develop automaticity better when learning under some conditions than others. In particular, classic work by

Schneider and Shiffrin (1977; Fisk Ackerman & Schneider, 1987) showed that only tasks for which there is high *consistency* between the mapping of events in the world and appropriate actions can develop total automaticity (and hence demand no resources). An example of such consistency is flight control without turbulence, in which a given action on the stick will be guaranteed to produce nearly the identical aircraft response every time given the same conditions (e.g., aircraft cargo weight and termperature/humidity/pressure) and within the same aircraft dynamics type.

However unlike flight control (the *aviate* tasks), many other aviation tasks do not provide the opportunity to acquire skills consistently, particularly many decision tasks; because the appropriate decision may depend heavily on the context or conditions in which the decision is required, which can vary markedly as would be expected in any complex domain. For example, the decision to fly on or turn back may depend not only on the weather, but also the fuel remaining or conditions at the different airports. Furthermore, appropriate decisions also depend on future conditions. Not only can information about the current situation be incomplete, future conditions are often imperfectly predictable, and hence provide an inconsistent context to which pilots must actively adapt (for a description of adaptive skill, see Ward, Gore, Hutton, Conway, & Hoffman, 2018). In short, many aviation decisions simply cannot be automatized and will always be resource-demanding, independent of the level of pilot expertise.

Knowledge. Just as reduced resource demand in consistently mapped tasks is a signature of experience producing expertise, so also is the increase in knowledge about aviation. Such increase allows both more rapid and accurate retrieval of facts and procedures with experience. In air traffic control, the amount of time spent at a particular facility is one of the greatest predictors of expertise, allowing the controller to understand all the particular quirks and features of the relevant airspace (Seamster, Redding, & Kaempf, 1997; Wickens et al., 1997). Studies have revealed that not only does the amount of knowledge increase with experience, the qualitative nature of knowledge organization becomes more sophisticated (Schvanevelt, 1985; Sherry & Polson, 1999).

Expertise in General Flight Performance

Hardy and Parasuraman (1997) argued that domain independent knowledge (i.e., used in domain-general cognitive functioning) and pilot's characteristics (i.e., domain-specific expertise) collectively determine general flight performance. Whereas most of the empirical studies report a close relationship between flight experience and basic flying skills, several cognitive ability factors have been inferred to mediate this relation such as time-sharing ability (Tsang & Shaner, 1995), speed of processing (Taylor et al., 1994), attention (Knapp & Johnson, 1996), and both psychomotor ability and general intelligence (*g)* (Caretta & Ree, 2003). Yakimovitch et al (1994) were among the very first to use a method to investigate these complex interactions between individual, expertise and flight performance. Their approach administered a battery of cognitive tests (e.g., Cogscreen-AE) and showed that it was predictive of flight parameter violation in real flight conditions. Following this approach of testing battery correlations with flight performance, Taylor and colleagues (2000) found that speed of processing, working memory, visual associative memory, motor coordination, and tracking abilities explained 45% of the variance of the flight simulator performance.

More recent studies have been able to replicate and expand these findings regarding processing speed (Kennedy et al., 2013; Tolton, 2014; Van Benthem & Herdman, 2016), working memory (Causse, Dehais, Arexis, & Pastor, 2011; Causse, Dehais, & Pastor, 2010; Tolton, 2014; Van Benthem & Herdman, 2016), tracking ability (Tolton, 2014), as well as visual attention allocation, cognitive flexibility (Van Benthem & Herdman, 2016) and logical reasoning (Causse, Dehais & Pastor, 2010). These were all positively correlated with to the ability to maintain flightpath and keep control of the aircraft.

In contrast to the previous studies however, Causse, Dehais and Pastor (2010) did not report any relationship between basic reaction time speed and flight performance, a conclusion echoing that of Caretta and Ree (2003). In contrast, Johnston and Catano (2013), reported only limited success of cognitive ability tests to predict success in Canadian military aviation training. In reviewing pilot selection test batteries Damos (1996) concluded that, collectively, these results showed only a limited ability to predict expert flight performance. In sum, although some studies show a positive correlation between cognitive ability and expert performance, the correlations are low, although sometimes significant ($p < .05$) between $r = .15$ and $r = .40$ (see Causse, Matton, and Del Campo, 2012). We now turn to the sources of expertise in the four more specific non-technical tasks.

Situation Awareness

As we might expect, each level of SA (noticing, understanding and predicting) in experts depends on different types of skills and abilities (Sohn & Doane, 2004; Wickens, 2007). At level 1, as we describe in detail below, visual scanning strategies are a major component (Wickens McCarley et al., 2008). At level 2, knowledge is critical for understanding (Sohn & Doane, 2004). And at level 3, because of the critical cognitive demands of projecting, there is a vital role for working memory as well as knowledge. We now describe each of these levels in more detail.

Visual scanning and level 1 SA. The monitoring of the flight parameters on the flight deck is a key issue for flight safety. The National Transportation Safety Board (NTSB) and the International Civil Aviation Organization (ICAO) that deficiencies in monitoring were a causal factor in most of the major recent civilian accidents (NTSB, 2013; UK Civilian Aviation Authority, 2013). Jones and Endsley (1996) determined that 755 of Air Force aircraft mishaps resulting from LSA, resulted from the breakdown of level 1 SA. Indeed, the volume of information that needs to be dynamically processed can overwhelm human operators and lead too poor situation awareness with regards to primary flight parameters. Several eye tracking studies have revealed that more experienced pilots have developed specific scanning strategies, different from novices, to ensure better awareness and flying performance (Kim, Palmisano, Ash, & Allison, 2010; Kirby, Kennedy, & Yang, 2014; Li, Chiu, & Wu, 2012; Ottati, Hickox, & Richter, 1999; Robinski & Stein, 2013). See also the comprehensive review of pilot scanning studies by Ziv (2017). As an example, a vast majority of studies revealed that experienced pilots exhibited shorter dwell times on the instrument displays but checked them more frequently (Bellenkes, Wickens, & Kramer, 1997; Kasarskis, Stehwien, Hickox, Aretz, & Wickens, 2001; Kramer, Tham, Konrad, Wickens, & Lintern, 1994; Li, Chiu, Kuo, & Wu, 2013; Sullivan, Yang, Day, & Kennedy, 2011; Tole, Stephens, Vivaudou, Ephrath, & Young, 1983). These finding suggest that expertise is associated with more efficient visual scanning, that is, greater skill at extracting relevant information in a shorter amount of time.

Some explanations may rely on the more experienced pilot's qualitatively different visual search pattern than novices and the proficiency of expert's mental model of their aircraft dynamics. For example, Bellenkes et al (1997) found that more experienced pilots scanned predictive instruments more than novices, as if they were *looking ahead* of the aircraft. Wickens, McCarley et al. (2008) noted that those pilots who showed greater adherence to the prescriptions of an optimal priority-driven scan model were more proficient in detecting possible traffic conflicts, hence linking differences in level 1 SA to expertise in the navigational component (hazard avoidance) of pilot performance. Schriver, Morrow, Wickens, and Talleur (2008) found that more experienced pilots, during simulated in-flight failures, both made better decisions and spent more time fixating on more relevant instruments. Here there was a link between experience and expertise in decision making, mediated by level 1 SA. The scanning patterns of more experienced pilots has also been shown to be more robust and less affected by increased workload and stress (Tole et al., 1983) and also to be more flexible to adapt to contingencies (Bellenkes et al., 1997).

Despite evidence that pilots improve their visual scanning with practice, some eye tracking studies have pointed out the importance of inter-individual differences with regard to visual abilities and level 1 situation awareness. For example, a study in a motion simulator revealed that dwell time on the landing gear indicator, but not flight experience, was predictive of the ability to detect an auditory landing gear alarm (Dehais et al., 2012, 2013). This study is in line with previous research demonstrating that the detection of unexpected events might be compromised by inadequate scanning and focused attention (Alexander &

Wickens, 2006). Li, Chiu and Wu (2012) found that specific scanning strategies led pilots to have a better situation awareness of an hydraulic failure independently of the level of experience. Moreover, their study revealed that dwell time on relevant instruments such as airspeed strongly mediated experience to optimize fuel consumption and flight duration.

Individual differences in scanning strategies have also been found to discriminate *good* versus *poor* flight performance during critical flight phases such as landing (Gray, Navia, & Allsop, 2014). Lefrancois, Matton, Gourinat, Peysakhovich, and Causse, (2016) found that pilots who had an inadequate dwell time on the attitude indicator were more likely to face an unstabilized approach and had to perform a go-around. Correspondingly, Reynal, Rister, Scannella, Wickens and Dehais (2017) observed that higher dwell time on the attitude indicator and lower fixation time on the navigation display was associated with poor awareness a destabilized approach and the resulting necessity to perform a go-around. Regarding this latter flight phase, crews whom Pilot Monitoring spent more time glancing on the speed indicator exhibited better flightpath management (Dehais, Behrend, Peysakhovich, Causse, & Wickens, 2017).

Our review failed to identify studies in air traffic control where individual differences in scanning strategies were specifically associated with performance differences. The only study located (Hasse, Grasshoff, & Bruder, 2012) revealed null results. Part of the challenge here is the more ill-defined (compared to the cockpit) designation of specific areas of interest at the controller work station for quantifying controller scanning.

Understanding and predicting: Levels 2 and 3 SA. In reviewing this literature, we combine research on levels 2 and 3 SA, because some researchers do not distinguish between them, and in any case, the borderline between what is happening (level 2) and what will happen (level 3) is a very fuzzy one. To illustrate, in a collision avoidance situation in which the pilot is in a state of predicted conflict (understanding current state), this state is indistinguishable from saying that the pilot *will* collide (prediction**)** (if a maneuver is not initiated)**.** Sohn and Doane (2004) found that experience (flight hours) was a strong predictor of aircraft state awareness, a finding consistent with that of Bellenkes et al (1997) who examined the frequency of looking at predictive instruments. It certainly makes sense that greater experience provides better knowledge and a better mental model of flight dynamics, hence allowing the pilot to more easily seek and absorb incoming information from appropriate sources. Sohn and Doane also found that SA was higher for pilots who had higher visualization skills and a greater capacity of long term working memory (LTWM; Ericsson & Kintch, 1995; see Chapter on *The Classic Expertise Approach*, Gobet, this volume). This latter construct—described as a retrieval structure-based mechanism that permits the limits of working memory to be circumvented—lies at the intersection of working memory and long term memory. Those who have developed LTWM skills have essentially developed the ability to rapidly access and retrieve material regarding changing state, even if that material is not being actively rehearsed.

Sulistwawati, Wickens, and Poon (2011) observed that spatial ability and general working memory capacity predicted situation awareness in air force fighter pilots, and Caretta and Ree (1996) observed a corresponding correlation of working memory capacity with the situation awareness of fighter pilots as rated by their superiors. Importantly, Caretta and Ree found that psychomotor performance and personality tests did not predict higher rated SA for their military sample.

Of the above studies, Sulityawati et al. explicitly distinguished predictors of level 2 from level 3 SA, observing that only level 3 expertise was uniquely predicted by reasoning and logic ability. Furthermore they found that pilots with high level 3, performed better in simulated air to air combat scenarios, but level 2 SA was not a significant predictor of performance here. Endsley and Bolstadt (1994) found that Levels 2 and 3 SA of fighter pilots correlated with spatial skills, perceptual speed and pattern matching ability.

In air traffic control, Durso, Blekely, and Gronland (1996) examined the speed and accuracy of simulated traffic management. The better performing novices (i.e., those developing greater expertise) showed higher cognitive abilities of spatial working memory, perceptual closure and need for cognition. Furthermore a test of controller SA developed by the authors added to the prediction of performance above and beyond those cognitive abilities. Unlike Sohn and Doane (2004), their test was not explicitly designed to test LTWM theory (as with Sohn & Doane, 2004), but the authors drew similar conclusions.

In conclusion, increases in memory capacity, both working memory and LTWM are associated with higher situation awareness. In the case of LTWM, this is consistent with the findings that experts in other domains possess greater LTWM skills (e.g., see Suss & Ward, 2015, 2018; Ward et al., 2013). In at least one study, higher SA was found to be directly associated with increased aviation flight performance.

Decision and Judgment

Good aviation judgment depends on good situation awareness but is distinct from it in its focus on the specific choice or action to be generated and then taken on the basis of a dynamic situation assessment. Ward et al. (2013) referred to decision making and the situation assessment process (i.e., sensemaking) as two reciprocal sides of the same dynamic system (e.g., Neisser, 1976; for a model of how these two processes work collectively to bring about adaptive performance, also see Ward et al., 2018). Hence, we might expect the quality of aviation decision making to be driven by some but not all of the factors that drive SA. We might also expect that decision making is driven by factors that are uniquely related to the choice process; such as generating options for action, based on past experience.

Experimental studies of expertise in pilot judgment and decision making have generally taken two forms: Discriminating those who make *good* decisions from those who make poor decisions in a particular context (such as the poor decision to continue the flight in poor weather), or assessing the characteristics of good pilot judgment in general (rather than in a particular context). In the former case, we assume that greater expertise is associated with those who make the better decision.

Good vs poor decisions. Several investigations have looked specifically at the tendency to make a poor judgment and fly on into deteriorating weather conditions, when the better choice is to turn back given the pilot's lack of qualifications. Several studies have indeed found that greater experience (i.e., more flight hours) supports better decision making in this context (Goh & Wiegmann, 2001; Hunter, Martinussen, Wiggins, & O'Hare, 2011; Wiggins & O'Hare, 1995; 2003; Wiegmann, Goh, & OHare 2002; Johnson & Wiegmann, 2015). However, Wiggins and Bollwert (2006) found better decision making to be more highly correlated with recency in flight experience (i.e., last 60 days) than with overall flight hours. A major reason why experience provided an advantage is that those with more experience tend to employ the strategies of seeking and interpreting cues in the weather environment. These cognitive activities (seeking, interpreting) are closely related to, if not the same as, the expert's advantage in level 1 and 2 SA, respectively.

Johnson and Wiegmann (2013) qualified that it was not purely the amount of flight hours that distinguished expert pilots making good decisions from those at a lower level of proficiency making poorer decisions. Rather it was the amount of time actually flying in poor weather that predicted decision quality. This implies a note of caution in simply using overall hours as a proxy for experience. Goh and Wiegmann (2001) observed that those who chose to continue flight when it was inappropriate to do so provided higher ratings of their own skills and judgments; a finding that might implicate a greater degree of overconfidence. We note however, that none of the researchers from this class of studies examined the influence of individual differences in, for instance, cognitive ability on judgment and decision making.

To complement research on the decision to fly on into bad weather, a second type of research discriminating good from poor choices has examined the choice to continue with a landing under ill-advised circumstances. Several behaviors describe the kind of factors that help avoid such poor decision making. For instance, as described earlier, those who did not choose to continue under sub-optimal conditions (i.e., chose to go-around), employed more efficient scanning strategies (e.g., higher number of and shorter fixations on information that permitted insight in to upcoming events; see Reynal et al., 2017) . Good decision makers had higher working memory capacity and greater attentional flexibility (Causse et al., 2011a), were better at risk assessment (Hunter et al., 2011), and exhibited lower impulsivity (Causse et al, 2011b, Behrend, Dehais, Koechlin, 2017). Subsequent research has also shown that when monetary incentive and uncertainty were manipulated in the helicopter landing decision task, risky decision makers exhibited lower activation of the prefrontal areas (i.e., dorso-lateral prefrontal cortex and anterior cingulate cortex) than good decision makers. These areas signify rationality (Causse et al., 2013). In a related study, Adamson et al. (2014) found that lower activity in the caudate nucleus was associated with higher landing decision accuracy in instrument meteorological condition. Unfortunately, however, how these differences are moderated by individual differences in expertise remains relatively unchartered, specifically when examining performance on an aviation task (cf. Hunter et al., 2011). Further, none of the studies of landing decisions appear to have associated decision quality with the differences in experience (e.g., number of flight hours).

Overall decision quality. The more general approach to measuring expertise in pilot decision making, going beyond a particular decision (e.g., to land or go-around) is illustrated by two classes of studies. As an example of the first type, Stokes and his colleagues developed a pilot judgment trainer/evaluator simulator called MIDIS, which presented various decision scenarios to pilots and emplyed skilled flight instructors to evaluate their choices of action in terms of decision quality (Barnett et al.,1987; Stokes, Kemper, & Marsh, 1988; Stokes et al., 1987; Wickens, Stokes, Barnett, & Hyman, 1993). Barnett et al., (1987) observed that within a cohort of more experienced pilots, better decisions were made by those with higher working memory capacity. Likewise, Stokes et al. (1988) found that experts generally made more optimal choices; for example turning back when it was appropriate to do so. Results from the other two MIDIS studies in which pilots with different levels of experience (i.e. more vs. less flight time) were compared either found no difference in decision quality between groups, or ambiguous results (i.e., differences on some metrics but not other; Stokes et al., 1987).

As noted above, Schriver et al. (2008) examined experience differences in pilot decision making following in-flight failures in a simulator, a skill heavily dependent upon diagnostic ability and cue seeking. As a consequence of seeking different cues (e.g., oil pressure indicator, airspeed) by those at a lower level of proficiency, more experienced pilots' decisions were superior in both speed and accuracy.

The second type of general decision quality study has examined non-experimental aspects of data. Rebok et al (2005) studied a large number of *violations* by air taxi pilots, where a violation was defined as an intentional decision to not follow or deviate from aviation rules. The authors found that fewer violations (i.e., *bad decisions*) were committed by pilots with more than 5000 flying hours. However among this group, there was no tendency for violation rate to decrease with additional flight experience.

In a related study, Hunter (2006) measured pilots' perception of perceived risk of different flight scenarios, as a function of their flight certification category, and observed that pilots in more advanced categories (e.g., transport pilots) who were, therefore, more experienced, generally perceived lower risk. It is not clear whether such pilots simply have greater confidence in their judgment because of greater proficiency, or rather, perhaps have greater overconfidence in their abilities. This finding potentially echoes that of Goh and Wiegmann (2001) and is consistent with other decision making research, which suggests that that higher levels of decision making experience often fosters increasing levels of overconfidence (Kahneman, 2011; Wickens Hollands et al., 2013).

Finally a pessimistic view of the relationship between experience and judgment quality was offered by the data of McKinney (1993) who examined the quality of professional's decision outcomes. Professional fighter pilots' quality of decision making following Air Force aircraft mishaps was analyzed by two experienced pilots.. No differences in quality were observed as a function of years of experience. Furthermore, McKinneys data revealed that those pilots flying in the leadership position exhibited poorer quality decisions, a finding McKinney attributes in part to greater overconfidence of those leads and partly to their lack of habit of soliciting information from others.

The absence of an experience effect is consistent with two other observations made by decision scientists on the effects of experience on decision making in other contexts.. Einhorn and Hogarth (1978) have identified relatively poor learning (i.e., limited improvement with experience) with respect to their decision making because the feedback is often delayed. Feedback in many real world contexts is often misleading in an uncertain world because poor decision sometimes produce (luckily) good outcomes, and vice versa (i.e., good decisions can have poor effects). Following the earlier research of Shanteau (1993), Kahneman (2011; Kahneman & Klein, 2014) examined the characteristics of professions in which experience does not produce expertise in (i.e., better) decision making and judgment and argued that the unpredictable aspects of such environments, and the resulting limited or challenging opportunities to learn from feedback, are primary reasons for this disconnect (for similar effects in healthcare, see Ericsson 2004; Ericsson, Whyte, & Ward, 2007). Given the complexities of many aviation environments, it is understandable that this environment may, sometimes, result in only a loose association between expertise and experience.

As reviewed above few researchers have directly examined these kinds of decisions as a function of cognitive ability differences. Those that have, have observed that any such differences are not reliably predictive of the choices made by pilots. The ability to predict expertise in decision making on the basis of experience appears to grow increasingly problematic as we move from specific in-context decisions (e.g., flying through bad weather, inappropriate landings, or inaccurate diagnosis of system failures) to more generic context-independent evaluations of the process. The effect of experience therefore appears to be to support seeking out relevant perceptual cues (e.g., Schriver et al., 2008), not necessarily a reliance on superior capacities.

Cockpit Task Management.

Surprisingly little research has been carried out on experience and expertise in aviation cockpit task management (Loukopolis et al., 2009; Chao, Madhavan, & Funk, 2003). The focus of this research is distinct from scanning, in that it defines how one switches attentional resources between tasks, rather than how the eyeball switches between sources of information. It is distinctive from much attention research in that it examines attention's sequential, rather than its parallel properties (Wickens, Gutwiller, & Santamaria, 2015). In one study Wickens and Raby (1995) imposed sudden high workload on advanced student pilots doing a landing approach. The distinguishing feature of expertise between those performing best (in terms of flight path deviations) and those performing worst was that the former group scheduled higher priority tasks at more appropriate or optimal times. Similar findings in a flight simulator study were reported by Laudemann and Palmer (1995). Neither study however examined differences in experience, nor correlated task management strategies with individual differences in cognitive ability.

Although basic research has correlated differences in basic attentional functioning with attention management strategies in multi-tasking environments, this has not been done in an aviation context, let alone with consideration of level of proficiency in this domain. Future aviation expertise research should examine this issue further.

Crew Resource Management.

Crew resource management, defines the coordination among teams (pilot, copilot, ATC) in, typically, dealing with in-flight emergencies or unpredicted events. While crew experience and CRM are beyond the scope of the current chapter (see Salas et al., 2010), one study of voice communications is directly relevant to both the non-technical skill of CRM and to the fourth task on the pilots' ANCS hierarchy: Communications. In this study, Morrow et al. (2003) found that experienced pilots showed better recall of typical ATC communications information than did non-pilots. However, there was little evidence that within the pilot population, increasing experience led to better recall. But for all groups, superior performance on communications recall was, expectedly, associated with greater working memory capacity and greater spatial ability. The latter benefit can be attributed to the fact that although numerical symbolic information was communicated, its interpretation was in terms of spatial locations and trajectories within the 3D airspace.

Training and creating expertise in non-technical aviation skills.

If experts perform better than novices in non-technical skills, an important issue is whether there are particular training modules available in these skills to *shortcut the trajectory* from novice to expert aviation professional. We examine whether their application has documented any success via positive transfer to more in-context aviation tasks. Here the evidence is scant and mixed. Regarding crew resource management, a host of CRM training programs have been adopted by nearly all of the American and European airlines; but a meta-analysis by Salas et al. (2006), concluded little consistent evidence for positive transfer. Regarding cockpit task management, Gopher and his colleagues have demonstrated some success of using the Space–Fortress multi-task video game to develop attention management skills that appeared to improve the chances of Israeli Air Force pilots to become qualified for the highest proficiency fighter pilot slots. Regarding decision making, other researchers (e.g., Walmsley & Gilbey, 2017) have developed specific aviation decision training modules (e.g., MIDIS: Stokes et al., 1988), but these have not been documented to transfer to better decision making in more remote contexts beyond the MIDIS simulator itself.

Regarding situation awareness, Endsley and Robertson, (2000) and (Endsley, & Garland, 2000) have discussed the need for such training but very few studies have proposed and evaluated indirect training for this important non-technical skill. For example, two PC-based situation awareness training programs were respectively implemented for navy cadets (Strater et al., 2004) and general aviation pilots (Bolstad, Endsley, Costello, & Howell, 2010). These studies failed to report strong evidences of situation awareness improvement. Only two situation awareness modules programs were developed for airlines pilots (Hoermann, 2003) and airline student pilots (Gayraud, Matton, & Tricot 2017). The results of these two studies disclosed better performance and situation awareness scores for the experimental versus the control group when confronted with scenarios in simulated flights. The findings of these studies should encourage more research to define and test training solutions to enhance situation awareness ability and other non-technical aviation skills such as scanning as a means to potentially accelerate the acquisition of expertise.

Conclusions

In conclusion expertise in aviation is certainly multi-dimensional, a complex mix of experience, abilities and strategies, and this situation reflects the complex mix of technical and non-technical skills required. It is important to note too that within the field, there is not the same sort of competition to identify *the best* pilot that exists in other domains of performance (the exception being competition in university aviation flight teams). Although military aviation training and selection does sometimes refer to those selected to be fighter pilots as "the elite", it is hardly fair to characterize them, as a class, as experts because their skills for high proficiency may be quite different from those demanded by the transport pilot, or helicopter pilot.

A further challenge for defining expertise in aviation arises from the emerging dominance of flight deck automation. This tends to level the playing field of flying skills, except on those rare and unexpected occasions when automation fails (Wickens, 2009) and here, the better performing pilot or controller (i.e., the *expert*) may, ironically, be the one who has greater proficiency performing without automation, so that graceful recovery can be accomplished.

Ultimately one can argue that what truly defines expertise in aviation is the guarantee of safety. But this is an exceedingly difficult commodity to assess; perhaps defined by wise decisions to avoid unsafe conditions and possessing the non-technical skills to escape those conditions should they unexpectedly be thrust on the pilot. But experience in making the former decision, as we saw, does not necessarily lead to competence, and the occurrence of the latter decision is, fortunately, quite rare but hence hard to reliably assess.

Hence, we see a strong need for research to continue to examine these differences in expertise defined by aviation proficiency, where and however they can be found, and correlate them with abilities, strategies (i.e., maintaining SA, scanning) and, indeed experience, to continue compiling these in a systematic way. We hope that this chapter has provided a foundation for this effort.

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