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Cognition and Flight Performance in Older Pilots

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The authors reviewed studies of cognitive proficiency and flight performance. Age-group differences were found in pilots in perceptual-motor skills and memory and, to a lesser extent, in attention and problem solving. Flight experience does not alter this age-related decline, with the possible exception of the metacognitive skill of time sharing. Age-group differences in flight performance are most evident in the secondary task of air traffic control communications. Age-related differences in current measures of pilot cognition are minimally predictive of primary measures of flight performance (flight simulation and accident rates). A model of cognition and flight performance is proposed involving higher order factors that tap into pilot knowledge structure, including mental workload and workload management, mental models, and situation awareness.

The cognitive changes that accompany adult aging have been extensively examined in studies comparing the performance of young and older adults on laboratory psychological tasks (e.g., Craik & Salthouse, 1992). Older participants in these studies typically are retired adult volunteers in the general population. Given the continued aging of the adult population (U.S. Bureau of the Census, 1995), however, there is a renewed impetus, for safety and practical reasons, to examine the older adult in a variety of typical life situations including job performance. The relation between cognition and everyday activities and work has been investigated in such areas as medication adherence (Park, Morrell, Frieske, Blackburn, & Birchmore, 1991), use of automatic teller machines (Rogers, Fisk, Mead, Walker, & Cabrera, 1996) and other technologies (Czaja, 1997), driving (Parasuraman & Nestor, 1991), and commercial flight operations (Morrow, 1996). The focus of this review is on the flight performance of older pilots.

When aviators first took to the air following the Wright brothers' successful powered flight at the beginning of this century, piloting demanded considerable physical and perceptual-motor skills. In contrast, pilots today must rely primarily on high-level cognitive skills such as decision making, planning, and appropriate management of their workload. For example, modern commercial aircraft have been designed to be highly automated. This has resulted in significant changes, both quantitative and qualitative, in the cognitive demands that flying imposes on pilots (Bainbridge, 1983; Parasuraman & Mouloua, 1996; Sarter & Woods, 1994; Wiener, 1988). Such changes have created opportunities for different kinds of human error and, in fact, 50% to 75% of fatal aircraft accidents (both civilian and military) are due to human error[1] (Baker,

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[1] We include in the term "human error" not just

Lamb, Li, & Dodd, 1993; Billings & Reynard, 1984; Vyrnwy-Jones, 1985). Perceptual-motor skills—for example, maintaining the flight path in turbulence, or split-second responding to avoid collision—are still important, particularly in military aviators, but the physical demands of flying have decreased, whereas the cognitive demands have concomitantly increased.

Because cognition plays an increasingly larger role in the piloting of modern aircraft, understanding the impact of age-related changes in cognition on pilot performance becomes correspondingly more important. It is well documented that some (but not all) cognitive abilities decline with age in adults (Craik & Salthouse, 1992). Information-processing speed, for example, slows, and the capacity to hold information in working memory may also decline with age (Birren & Schaie, 1990; Cerella, 1994; Salthouse, 1991a). Could age-related cognitive decline result in a loss of flying proficiency in older pilots? The question is important for at least two reasons: (a) there are more older pilots than before, particularly in general aviation (Bruckart, 1992), reflecting the aging of the adult population (U.S. Bureau of the Census, 1995); and (b) the Federal Aviation Administration (FAA) has a regulation commonly called the "Age 60 rule" that mandates the retirement of commercial airline pilots when they turn 60 years old (Federal Register, 1978).

Understanding the Cognition–Performance Link in Older Pilots

Although seemingly straightforward, the question of age-related cognitive decline and flight performance in older pilots involves some intricacies. To begin with, the relationship between age-related cognitive decline and job performance is complex (Czaja, 1990). Cognitive ability (including perceptual-motor skills) is moderately associated with job proficiency (see Hunter & Hunter, 1984, for a review). This is also true for pilot performance, at least during training (Martinussen, 1996). But many studies have failed to find a negative relationship between age and job performance (Davies & Sparrow, 1985; McEvoy & Cascio, 1989; Van Zelst, 1954). Perhaps the job-related experience or occupation-specific knowledge of older workers compensates for any age-related cognitive decline (Salthouse, 1994a).

This raises the question of how expertise and age interact, an issue that has been examined extensively in the cognitive aging literature. Expertise sometimes ameliorates the effects of aging, but not always (Ericsson & Charness, 1994; Salthouse, 1994a). In studies of pilots, flight expertise or experience and pilot age are often confounded, making comparisons between younger and older pilot performance potentially difficult to interpret.

Another reason for a lack of a relationship between age-related cognitive decline and job performance could be that the simple, static measures of cognitive functioning typically obtained in laboratory tests may not be representative of the more complex and dynamic cognitive processes required in real-world tasks. We identify this as a major limiting factor in drawing generalizations about older pilot cognition and flight performance. A model discussing how these higher order processes are linked to flight performance is proposed.

Finally, although cognitive ability can be relatively easily evaluated, assessing flying proficiency in pilots is not so simple. Should one measure simulator performance, observe actual flights, analyze incidents, or investigate accidents? Is a single index of pilot performance useful? Or is it more likely that a complex aggregate of flight performance measures is required? For example, in an early study, 21 "critical requirements" for the job of a commercial airline pilot were determined on the basis of accident and incident reports and flight-check records (see Table 1; Gordon, 1949). Each critical requirement or component was named for a group of related pilot acts. It is instructive to examine these requirements or component abilities—despite the datedness of the study—because they were based not a priori on just face

errors made by pilots, but also those potentially attributable to human designers of flight equipment and software, as well as to managers, supervisors, and regulators who define and enforce procedures concerning operator use of automation technology (see Parasuraman & Riley, 1997).

Table 1
Component Abilities of Commercial Airline Pilot Performance Determined by Frequency of Errors Extracted From Accident Reports, Critical Incidents, and Flight Checks

Component ability	Frequency of errors			
	Accidents	Incidents	Flight checks	Total
Establishing and maintaining angle of glide, rate of descent, and gliding speed on approach to landing	47	41	11	99
Operating controls and switches	15	44	33	92
Navigating and orienting	4	39	19	62
Maintaining safe airspeed and attitude, recovering from stalls and spins	11	28	18	57
Following instrument flight procedures and observing instrument flight regulations	5	27	13	45
Carrying out cockpit procedures and routines	7	31	4	42
Establishing and maintaining alignment with runway on approach or takeoff climb	3	31	5	39
Attending, remaining alert, maintaining lookout	14	23	1	38
Utilizing and applying essential pilot information	0	19	18	37
Reading, checking, and observing instruments, dials, and gauges	1	26	7	34
Preparing and planning of flight	2	27	3	32
Judging type of landing or recovering from missed or poor landing	1	23	8	32
Breaking angle of glide on landing	1	25	5	31
Obtaining and utilizing instructions and information from control personnel	3	21	0	24
Reacting in an organized manner to unusual or emergency situations	0	17	7	24
Operating plane safely on ground	7	15	1	23
Flying with precision and accuracy	0	7	15	22
Operating and attending to radio	0	7	10	17
Handling of controls smoothly and with coordination	0	6	8	14
Preventing plane from undue stress	0	5	7	12
Taking safety precautions	2	5	4	11

Note. Based on "The Airline Pilot's Job," (Gordon, 1949).

value (which is sometimes done) but on factors found relevant to actual flight performance. As Table 1 shows, the component skills vary considerably in scope and complexity. An important point is that some of the more complex component abilities are difficult to examine in the laboratory, but they are still ultimately crucial in the assessment and prediction of pilot proficiency. One of the conclusions in this article is that examining potential age-related differences in these more complex skills is necessary to better understand the experience, proficiency, and limits of older pilots.

These complexities notwithstanding, to understand whether age-related cognitive decline is associated with poorer flight performance in older pilots is of both theoretical and practical importance. In this review, we examine several different aspects of age-related changes in cognition and flight performance among pilots. Although we refer to studies of cognitive aging in general, studies that examined pilots are emphasized. The scope of this review is framed in three questions. First, what are the age-related differences in pilot cognition? Second, what are the age-related differences in pilot flight performance? And third, what is the relationship between age-related differences in pilot cognition and age-related differences in flight performance? The first question was the primary topic of a previous review (Tsang, 1992). We review studies conducted since that time (and studies that were not included in that review), and we examine the influence of expertise, including flying experience, on age-related differences in cognition. We also review studies of flight performance in pilots.

Pilot Cognition and Aging

What are the age-related changes in pilot cognition? Although cognitive ability (including perceptual-motor skills) has been extensively examined in relation to military pilot selection and flight performance (Callister, King, & Retzlaff, 1996; Koonce, 1996; Olea & Ree, 1994) and will probably become more important in the routine medical assessment of civilian pilots (Mohler, 1993), it is surprising that few studies have actually compared basic cognitive ability in younger and older pilots. Age-related differences in cognitive task performance have been examined in relation to aviation-relevant factors (e.g., altitude, drugs, workload demands, etc.), but in many of these studies, the participant samples included nonpilots (e.g., Braune & Wickens, 1985; Fox, Eggemeier, & Biers, 1995) or participants that were merely the health equivalent (by passing the equivalent of a pilot's physical examination) of pilots (e.g., Collins & Mertens, 1988; Mertens & Collins, 1986; Mertens, Higgins, & McKenzie, 1983). These studies could not assess the impact of task-related experience or expertise on cognitive functioning. Because all pilots have flight experience and varying degrees of expertise, the applicability of performance data from nonpilots is limited. In addition, age, flight classification, pilot health, and task demands are all important factors in the interpretation and generalization of experimental results. This is particularly true with respect to the Age 60 rule, which has stimulated much aviation aging research (and fueled the angst of many older pilots). The Age 60 rule is discussed in a later section of this article.

Theories of Cognitive Aging

Many theories that account for age-related differences in cognition have been proposed. Although critical examination of all theories is beyond the scope of this article, five prominent theories of cognitive aging are briefly discussed, with their suggested implications for older pilot cognition and flight performance. It should be kept in mind that these theories are based on the cognitive performance of nonpilot young and older adults (and sometimes individuals with neurological deficits, e.g., due to dementia or frontal-lobe damage). Furthermore, some of these theories do not explicitly address the potential ameliorating effects of extended experience or practice in relevant skills (that a pilot might have) on the cognitive performance of the older adult.

Fluid versus crystallized intelligence. One theory of cognitive aging proposes that older adults decline in fluid intelligence but that crystallized intelligence remains stable or even improves (Horn & Cattell, 1966). Fluid intelligence is required for processing of relatively new information or information in a context of minimal meaningfulness, such as in many simple laboratory perceptual-motor and memory tasks. Crystallized intelligence refers to stored knowledge or to those processes that tap into the accumulated products of previous processing that are often overlearned or embedded in a meaningful context. A typical measure of crystallized intelligence is vocabulary. Much research evidence supports this distinction in the cognitive development of the elderly (for reviews see Salthouse, 1991b; for a critical assessment see Rabbitt, 1993).

According to this theory, older pilots, like other older adults, should experience a decline in fluid but not crystallized intelligence. If fluid and crystallized intelligence are represented by Digit Symbol (a standard measure of cognitive processing efficiency) and vocabulary performance on the Wechsler Adult Intelligence Scale—Revised (WAIS–R), then the prediction holds (see Table 2). The resulting effect on flight performance would depend on whether piloting makes greater demands on fluid or crystallized intelligence. The task of flying an aircraft includes components of both fluid and crystallized intelligence, but the relative proportion of these components necessarily changes according to situational demands. For instance, cruising at high altitude imposes minimal demands on fluid intelligence (e.g., the occasional monitoring of altitude or heading) and only routine demands on crystallized intelligence (e.g., having to know the schedule of a flight plan and the procedures of flying the aircraft). During an emergency situation, however, the demands on fluid intelligence could be extremely high, such

Table 2
Mean Scores on Digit Symbol and Vocabulary for Younger and Older Pilots

Study	Digit Symbol[a]		Vocabulary[b]	
	Young	Old	Young	Old
Tsang et al. (1995)	68.3	50.9*	—	—
Taylor, Dolhert, et al. (1994)	65.0	53.6*	62.4	65.6
Taylor, Yesavage, et al. (1994)	63.7	53.4*	62.8	65.5
Yesavage et al. (1994)	63.9	53.5*	62.6	65.6

Note. Digit Symbol and Vocabulary tests are from the Wechsler Adult Intelligence Scale—Revised (Wechsler, 1981). Dashes indicate that pilots in the Tsang et al. study were not given the Vocabulary test.
[a]Digit Symbol scores = the number of test items completed within 90 s; maximum score = 93. [b]Vocabulary scores = the number of correctly identified words; maximum score = 70.
*$p < .05$.

as when novel information (that does not necessarily fit into the pilot's mental model or schema of flying) must be quickly integrated and decided upon. The potential vulnerability of an older pilot should increase with an increase in the demands on fluid intelligence. However, if crystallized intelligence is called upon, the theory predicts little age-related decline. Furthermore, to the extent that crystallized intelligence develops as a result of experience, the fluid–crystallized intelligence theory includes the role of flight experience in potentially mitigating age-related decline.

Decline in inhibition. A prominent explanation for age-related differences in cognition is that inhibitory cognitive processes decline in older adults (Hasher & Zacks, 1988; Layton, 1975). Inhibition is proposed to be a mechanism that facilitates selective attention, and that a decline in inhibition results in the inclusion of irrelevant information into working memory, interfering with a variety of cognitive processes. The evidence for an age-related decline in cognitive inhibition includes a variety of interference-sensitive tasks showing performance deficits in older adults, such as the Stroop test, the stop paradigm, and negative priming (Dempster, 1992).

A possible cause for inhibitory decline in older adults is a normal age-related decline in frontal cortex functioning (Dempster, 1992; Rafal & Henik, 1994). Because this is considered a normal physiological decline, older pilots would be expected to experience the same age-related decline in inhibition (and frontal cortex functioning) as other older adults. There are serious implications if this kind of inhibitory decline exists at higher order cognitive processing levels such as strategy or procedure use. For example, developments in aviation technology, such as advanced automated systems, can produce changes in pilot routines, procedures, and flying strategies. Older pilots could have more difficulty adapting to a new system or inhibiting response procedures appropriate for an older system, which could be risky in an unusual, time constrained, or emergency situation. At the same time, older pilots are typically more experienced than younger pilots. However, theories of cognitive inhibition do not explicitly address the idea of extended experience or expertise protecting against inhibitory decline.

Reduction in processing resources. A popular concept in cognitive psychology is that of processing resources (see Navon, 1984). As the term implies, these resources are fundamental and necessary for cognitive processing, like the fuel for a working engine. Processing resources are also in limited supply. An explanation for age-related differences in cognition is that older adults experience a reduction in the requisite processing resources (Salthouse, 1985, 1988). Processing resources can be characterized as speed of processing, working-memory capacity, or attentional capacity. Speed of processing is treated separately in the next section.

Age-group differences in working-memory capacity have been found on a variety of measures, including digit span (Salthouse, 1988), the more difficult sentence span (Gick, Craik, & Morris, 1988; Light & Anderson, 1985), and other types of computation spans (Dobbs & Rule, 1989; Salthouse, 1990b, 1994b). Evidence of an age-group difference in attentional capacity includes the finding of older adults having more difficulty, or greater divided attention costs, when performing two difficult tasks simultaneously (Greenwood & Parasuraman, 1997; Hartley, 1992).

According to processing resource theories, pilots, like other older adults, should experience an age-related reduction in processing resources. Therefore, whether due to a reduction in working-memory capacity or attentional capacity, older pilots would be expected to exceed their processing capacity limit sooner than would younger pilots. Simplistically speaking, this means that if the processing demands of flying are relatively low or moderate, older pilots should be fine and perhaps perform no differently than younger pilots. However, if processing demands are unusually high, as during an in-flight emergency, then older pilots may be vulnerable.

A disadvantage of the processing resource theory is that independent measurement of resources has proven difficult, although the use of working memory capacity (Salthouse, 1985, 1988) and psychophysiological measures (Kramer, 1991) has been explored. As a result, processing resource theory has been criticized for circularity of reasoning (Navon, 1984). In contrast to this potential limitation, an advantage of resource theory is that it explicitly incorporates the impact of expertise, particularly as derived through practice. Extended practice is thought to reduce the processing resource demands of tasks through the development of automaticity (Schneider & Shiffrin, 1977). Kramer, Larish, and Strayer (1995) found that training with a variable priority technique led to automaticity of single task components during dual-task performance, with older adults benefitting more than younger adults in certain dual-task conditions.

Cognitive slowing. Slowing of all cognitive operations has been proposed as a general characteristic of adult aging (Birren, 1970; Cerella, 1994; Salthouse, 1985). Generalized cognitive slowing proposes that all cognitive operations are slowed by the same proportional amount. This account of age-related cognitive slowing is sometimes known as the complexity hypothesis or the Birren hypothesis. The evidence for this theory usually takes the form of a regression plot, where it is shown that across tasks of differing complexity, mean reaction time (RT) for older adults can be expressed as a linear function of young RT, with slope of between 1.3 and 1.7. Other theorists argue for *selective slowing,* for example, that cognitive slowing in older adults is more pronounced for response-related processes (Bashore, 1990; Hartley, 1992).

What does this mean for older pilots? According to the theory of generalized cognitive slowing, older pilots, like adults in general, will exhibit slowing of RT. Thus, proportional age-group differences in a variety of cognitive processing speed measures should be evident in pilots. The selective slowing theory predicts that older pilots should be differentially slower in response-related processes. Both theories predict that older pilots will have more difficulty under time pressure. According to the selective slowing version, older pilots will have the most difficulty reacting in an emergency only when having to make many overt (motor) responses.

Disuse. One theory proposes that cognitive decline in older age is due not to aging per se, but to unexercised cognitive abilities (Denney, 1984). The idea of cognition as a skill, where cognitive ability develops and is maintained with frequent use but withers away with disuse, is an ancient one and a traditional conceptualization in psychology (Pax, 1937). As an explanation for cognitive aging, evidence for this theory includes the differentiation of age-group differences on performance (or fluid) versus verbal (or crystallized) measures of intelligence. This is similar to the fluid versus crystallized intelligence theory of cognitive aging. However, a significant difference is that in the disuse theory, the processes that show decline are unexercised ones and not necessarily fluid intelligence processes. Thus older adults experience a decline in performance measures of intelligence because they do not frequently use them. Regular training or exercise in these skills, it is proposed, prevents their decline.

Therefore, the degree to which older pilots experience a cognitive decline depends on which cognitive skills they frequently use and which ones they ignore. This in turn would depend on the type of flying or the type of pilot. For example, active military pilots are more likely than general aviation (GA) pilots to routinely and intensely use verbal and performance (such as perceptual-motor) types of processing when flying. Military pilots should therefore show less decline in performance or fluid processing measures than nonpilots and GA pilots. Commercial airline pilots would be expected to preserve cognitive skills at a level somewhere between military and GA pilots. This is an optimistic theory in the sense that flying performance would not be expected to decline in older pilots, at least not until their performance potential is seriously compromised by physiological decline. Therefore, flight performance, and cognitive proficiency, would be related less to age and more to pilot experience (such as recent and total flying hours).

Summary of cognitive aging theories. The disuse theory is the only theory that predicts little or no change in cognitive ability in active older pilots. Four other cognitive aging theories predict that older pilots will experience age-related decline in cognitive ability, which could potentially negatively impact on flight performance. Older pilots would be expected to have deficits in processes of fluid intelligence, a decline in cognitive inhibition, a reduction in processing resources (working-memory or attentional capacity), and a slowing of cognitive processing speed. Some of these declines are relatively specific, such as inhibition. Other declines are more global, such as cognitive slowing, and they would be expected to have a more inclusive impact on pilot cognitive functioning. According to these four theories, age-group differences or age correlations in pilot performance would be expected on a variety of cognitive tasks. Two of the theories, however, fluid–crystallized intelligence and processing resource theory, provide for the possibility of extended flight experience amerliorating age-related cognitive decline. We now examine to what extent the empirical evidence supports the predictions of these theories.

Studies of Older Pilot Cognition

As can be seen in Table 3, the number of studies that have examined age-related differences in basic cognitive processes in pilots is relatively small. This is surprising given the number of articles that have discussed aging and aviation (Birren & Fisher, 1995; Dille, 1985; Halaby, 1962; Hyland, Kay, Deimler, & Gurman, 1994; McFarland, 1953; Mohler, 1961, 1963, 1985; Salive, 1994; Tsang, 1992). Among the few studies that did examine cognition in older pilots, a variety of pilots was examined including commercial, military, and GA pilots. As might be expected given the Age 60 rule, the upper age limit for older pilots was greater in the samples that included GA pilots. Several cognitive processes were examined, particularly in a few comprehensive studies (e.g., Glanzer & Glaser, 1959; Tsang, Shaner, & Schnopp-Wyatt, 1995; Szafran, 1969). Cognitive processes, especially as they pertain to aviation performance, can be categorized in a variety of ways (Braune & Wickens, 1985; Gopher, 1982; Hyland et al., 1994; Tsang, 1992; Wickens & Flach, 1988). We summarize the results of the cognitive aging studies in pilots around four cognitive processing domains: perceptual-motor skills, memory, attention, and problem solving–decision making (see Table 4).

Perceptual-motor skills. Perceptual-motor skills are fundamentally important to basic flight tasks such as take-off and climb, maintaining the

Table 3
Summary of Age and Pilot Type in Cognitive Aging Studies

Study	Pilot type	Age range	Age group mean: Young	Older	All
McFarland et al. (1939)	C	20–47	—	—	—
Glanzer & Glaser (1959)	C, M	20–50	—	—	—
Birren & Spieth (1962)	G	23–60	—	—	40
Spieth (1964)	G	23–59	—	—	—
Szafran (e.g., 1969)	C, M	20–60	—	—	—
Morrow et al. (1992)	V	—	30	66	—
Hyland (1993)	C	41–70	—	—	53
Morrow, Leirer, et al. (1994)	V	—	29	66	—
Taylor, Dolhert, et al. (1994)	G[a]	—	27	60	—
Taylor, Yesavage, et al. (1994)	G[a]	21–74	27	61	—
Yesavage et al. (1994)	G[a]	21–69	27	60	—
Tsang et al. (1995)	V	20–80	31	70	—
Callister et al. (1996)	C, M	—	24	44	—
Lassiter et al. (1996)	G	21–75	32	55	—

Note. Dashes indicate that data were not available. For pilot type, C = commercial (airline, transport, etc.); M = military (Navy, Air Force, etc.); G = general aviation; V = various (typically including commercial and general aviation pilots).
[a]We assume the pilots were general aviation; most pilots were instrument rated, but it is possible that some pilots had more advanced rating.

Table 4
Summary of Age Effects on Pilot Cognition

Study	Task/process	Age-related difference/ relationship?
	Perceptual-motor skills	
McFarland et al. (1939)	Serial RT test	Yes
	Domino test	No
Glanzer & Glaser (1959)	Object Identification	Yes
	Spatial Orientation	Yes
	Instrument Comprehension	Yes
	Reoriented Reading—Clocks	Yes
	Reoriented Reading—Words	Yes
Birren & Spieth (1962)	Continuous Serial RT	Yes
Spieth (1964)	Continuous Serial RT	Yes
	Digit Symbol	Yes
	Block Design	Yes
	Tactual Performance test	Yes
Szafran (e.g., 1969)	Visual Accommodation	Yes
	Dark Adaptation	Yes
	Pulsed Tone Threshold	Yes
	Continuous Tone Threshold	Yes
	Critical flicker fusion frequency	No
	Minimum perceptible interflash interval	No
	Visual Recognition Thresholds	No
	Choice RT	No
Morrow et al. (1992)	Object Rotation	Unclear[a]
	Block Design	Unclear[a]
Morrow, Leirer, et al. (1994)	Block Design	Yes
Taylor, Dolhert, et al. (1994)	Digit Symbol	Yes
Taylor, Yesavage, et al. (1994)	Digit Symbol	Yes
Yesavage et al. (1994)	Digit Symbol	Yes
Tsang et al. (1995)	Digit Symbol	Yes
	Horizontal Tracking	Yes
	Vertical Tracking	Yes
	Mental Rotation	Yes
	Memory	
Glanzer & Glaser (1959)	Code Memory	No
Spieth (1964)	Tactual Performance Test	Yes
Morrow et al. (1992)	Aviation Scenario Recall	Yes
	Sentence Span	Unclear[a]
Morrow, Leirer, et al. (1994)	ATC (visual) Readback	No
	ATC (auditory) Readback	Yes
Taylor, Dolhert, et al. (1994)	Digit Span	No
Taylor, Yesavage, et al. (1994)	Digit Span	No
Yesavage et al. (1994)	Digit Span	No
Tsang et al. (1995)	Digit Span	Yes
	Sternberg V-V manual	Yes
	Sternberg V-V verbal	Yes
Callister et al. (1996)	Digit Span	Yes
Lassiter et al. (1996)	Sternberg Memory Search—Manual	Yes

Table 4 (*continued*)

Study	Task/process	Age-related difference/ relationship?
	Attention	
Szafran (e.g., 1969)	Effect of noise on tone detection	No
	Effect of noise on visual detection	No
	Choice RT/memory load	Yes
	Choice RT/memory load, flicker	No
	Choice RT/verbal response	No
	Choice RT/verbal response with delayed speech monitoring	Yes
Tsang et al. (1995)	Vertical tracking/Horizontal tracking	Yes
	Mental rotation/Horizontal tracking	Yes
	Sternberg V-V manual/Horizontal tracking	No
	Sternberg V-V verbal/Horizontal tracking	No
Callister et al. (1996)	Divided attention test	Yes
	Dual task test	Yes
	Problem solving/decision making	
Glanzer & Glaser (1959)	Code learning	Yes
	Finding relationships	Yes
	Mechanical principles	Yes
	Orientation to new equipment	Yes
	Mathematical reasoning	No
	Numerical operations	No
	Reading comprehension	No
	Numerical approximation	No
Birren & Spieth (1962)	Trail Making test	Yes
Spieth (1964)	Trail Making test	Yes
Morrow et al. (1992)	Vocabulary	Unclear[a]
Morrow, Leirer, et al. (1994)	Vocabulary	Yes
Taylor, Dolhert, et al. (1994)	Vocabulary	No
Taylor, Yesavage, et al. (1994)	Vocabulary	No
Yesavage et al. (1994)	Vocabulary	No
Tsang et al. (1995)	Raven advanced Progressive matrices	No

Note. RT = reaction time; ATC = air traffic control; for Sternberg memory search tasks: V-V = visual presentation, verbal stimuli; manual = manual response; verbal = verbal response.
[a]Test was mentioned, but results were not provided.

flight path, final approach, and landing. Misperceptions while flying, such as altitude and attitude illusions, due to sloping cloud formations without a ground reference for example, also highlight the importance of perceptual skills in flying (Edwards, 1990). Accordingly, tests of perceptual-motor skills have historically played a central role in the selection and training of military pilots (Fitts, 1946; Fleishman & Hempel, 1956; Marquis, 1944; Office of the Air Surgeon, 1943) and to a lesser extent civilian pilots (Viteles, 1945). An early example of this special role is the examination, at the Army Aviation Ground school in 1917, of cadets on tests of simple auditory and visual RT, continuous choice RT, maze tracing, eye saccades and smooth pursuit, finger tapping, auditory difference threshold, and simple reaction learning (Yerkes, 1919). As mentioned previously, although modern cockpit automation has shifted the balance of requisite pilot skills to more cognitive and strategical tasks, tactical perceptual-motor skills are still important. Perceptual-motor skills remain central to the pilot selection research of the U.S. military (Griffin & Koonce, 1996). Sometimes a single perceptual dimension has been shown to be predictive (at least in a controlled environment) of pilot performance. For example, in a flight simulation study with experienced jet pilots, those with the most sensitive ability to detect visual spatial frequencies under different contrasts (a contrast sensitivity function; CSF) were able to spot the furthest away an obstructing airplane on the runway and abort a landing (Ginsburg, Evans, Sekuler, & Harp, 1982). Related to this CSF-related difference and perhaps important to flight performance is the finding of an age-related decline in CSF beginning after age 30 (Owsley, Sekuler, & Siemsen, 1983; Sekuler & Blake, 1994).

For many perceptual-motor skills across all types of pilots, younger pilots performed better than older pilots. Processing speed was a factor in many of the age-related differences reported. Older pilots have been shown to be reliably slower than younger pilots on the Digit Symbol test (of the WAIS, Wechsler, 1955, and the WAIS–R), a standardized test of mental proficiency. Age-group differences have been reported both for GA pilots (Birren & Spieth, 1962; Spieth, 1964; Taylor, Dolhert, Morrow, Friedman, & Yesavage, 1994; Taylor, Yesavage, Morrow, Dolhert, Brooks, & Poon, 1994; Yesavage, Dolhert, & Taylor, 1994) and for a mixed sample of pilots (Tsang et al., 1995; see Table 2).

Older pilots were also found to be slower than younger pilots in serial choice RT. In an extensive study of commercial airline pilots ($N = 200$), McFarland, Graybiel, Liljencrantz, and Tuttle (1939) reported a significant age-group difference in commercial airline pilots on the Mashburn Serial Action Test (Mashburn, 1934). This task, which required the coordination of stick and rudder movements in response to different patterns of lights on a panel, was considered a crude simulation of pilot psychomotor and decision-making performance. Task performance for each pilot was measured as the time to complete a series of 40 different pattern settings. Mean task completion time was found to increase from younger to older pilot groups (see Figure 1). Two other early and adjoining studies (Birren & Spieth, 1962; Spieth, 1964) examined a large sample of participants (age range = 23 to 60 years) who were either GA pilots or air traffic controllers (ATCs), or both ($N = 161$ and $N = 560$). Age significantly correlated (.59) with a composite response latency score from a battery of choice RT tasks (Psychomet, WAIS Digit Symbol, Trail Making test, etc.) (Birren, Riegel, & Morrison, 1962). Factor analysis of all the measures obtained revealed that age was most closely associated with a psychomotor speed factor (Birren & Spieth, 1962). Age-group differences were also found with young participants (age 23 to 39 years) faster than older participants (age 50 to 59 years; Spieth, 1964). An exception to these findings is the result of a study (reported in several overlapping articles) on a mixed sample of commercial and military pilots (Szafran, 1963, 1965a, 1965b, 1966b, 1966a, 1969). Szafran (1965a) reported that there was no significant difference in mean RT on a choice RT task between younger (253 ms) and older (262 ms) pilot groups. Notwithstanding this exception, the bulk of the evidence indicates that older pilots are

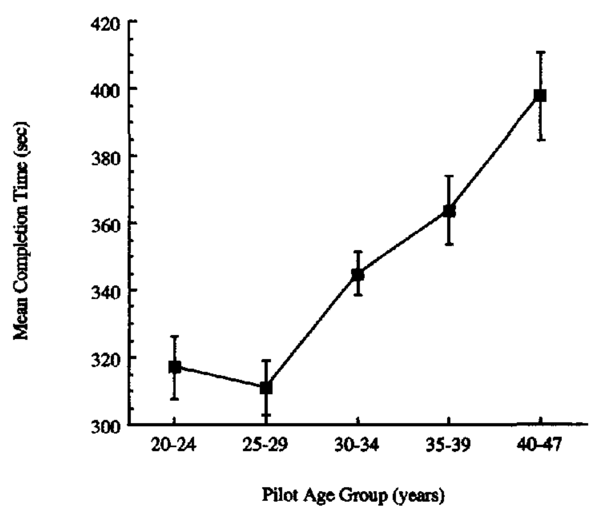

Figure 1. Mean completion time for commercial airline pilots on the Mashburn Serial Action Test (based on data from McFarland et al., 1939). Vertical lines represent standard errors of the means.

slower in perceptual-motor processing speed than younger pilots.

Age-related differences or relationships have also been reported for other perceptual-motor tasks. For example, in the Szafran (1969) study, age correlated with visual accommodation at short viewing distances (−.75) and with visual detection thresholds as a function of dark adaptation (.25 and .20 for alpha and terminal points). Auditory thresholds for pulsed and continuous tones were also higher for older pilots compared with younger pilots. However, in the Szafran study there were also no significant age-related changes in detection threshold of critical flicker fusion frequency and minimum perceptible interflash interval and recognition thresholds for tachistoscopic displays for simple stimuli such as shapes, numbers, letters, and words. For more complex perceptual-motor tasks, in a heterogeneous sample of pilots, older pilots performed worse (had larger deviations) than younger pilots on a horizontal tracking task and a vertical tracking task (Tsang & Shaner, 1995; Tsang et al., 1995). In a large sample of commercial airline and military pilots (N = 90 and N = 454, respectively), there were significant correlations between pilot age and several aviation-related tasks including object identification (−.29), spatial orientation (−.14), instrument comprehension (−.33), and reoriented reading clocks (−.09; Glanzer and Glaser, 1959).

In summary, age-related differences in perceptual-motor skills are apparent in a variety of pilot types. These differences appear to be less reliable in commercial airline and military than in GA pilots. For example, in the Szafran (1969) study, there was no significant age-group difference in various visual detection thresholds and in a choice RT task, and in the Glanzer and Glaser (1959) study, age correlations with task performance were at best of modest magnitude. Perhaps the expertise produced by the unusually high demands on commercial airline and military pilots compensates for the detrimental effects of aging on some aspects of perceptual processing speed and skill (this issue is examined in more detail later). On the other hand, the commercial airline pilots and certainly the military pilots in these samples were younger in general compared with other types of pilot samples (such as GA pilots), and at least in the Glanzer and Glaser study, the age range in the pilot sample was relatively restricted (20 to 50 years) compared with other aviation aging studies.

Memory. The many tasks of flying a plane often place demands on memory. It is important for the pilot not only to remember incoming information, such as ATC messages and instrument readings (involving short-term or working memory) but also to remember when to do things in the face of many competing distractions and to develop appropriate mental schemata or models about procedures and systems (memories that would be considered more long-term or prospective). Age-related differences have been reported for both working memory and long-term memory in pilots. For example, in a mixed sample of pilots, younger pilots had better scores on the Digit Span test, a standard measure of working memory, compared with older pilots (Tsang et al., 1995; see Table 5). In another study (Callister, King, & Retzlaff, 1996) where cognitive performance in a large sample of U.S. Air Force (USAF) pilot candidates (n = 512) was compared with that of commercial pilots (n = 584), digit recall accuracy was significantly higher in the younger USAF pilot candidates (89%) compared with the older commercial pilots (84%). However, in GA pilots, no such difference in Digit Span was found (Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994; Yesavage et al., 1994). These results may reflect the fact that age-group differences in digit span in the general population are typically small, as they are for older pilots (see Table 5). Short-term recall of

Table 5
Mean Scores on Digit Span for Younger and Older Pilots

Study	Digit Span[a]	
	Young	Old
Tsang et al. (1995)	8.9	8.0*
Taylor, Dolhert, et al. (1994)	9.2	8.5
Taylor, Yesavage, et al. (1994)	9.4	8.6
Yesavage et al. (1994)	9.4	8.8

Note. Digit Span tests are from the Wechsler Adult Intelligence Scale—Revised; (Wechsler, 1981).
[a]Digit Span scores reflect the longest sequence of digits that were recalled. Scores were averaged over the forward and backward versions of the test. Maximum score = 14. A score of 2 means that three digits were reliably recalled. A score of 14 means that nine digits were reliably recalled.
*$p < .05$.

sentences, which imposes a greater load on working memory, shows greater age-related decline in both pilots and nonpilots (Morrow, Leirer, & Altieri, 1992). Age-group differences in speed of access to working memory also exist. As with measures of processing speed in perceptual-motor tasks, older pilots have been reported to be slower than younger pilots on a variety of Sternberg memory-search tasks (Lassiter, Morrow, Hinson, Miller, & Hambrick, 1996; Tsang et al., 1995).

Pilot age-group differences in working memory are also dependent on stimulus modality. Morrow, Leirer, Altieri, and Fitzsimmons (1994) found that for an ATC communications task in which pilots had to read back a series of messages (concerning position, heading, altitude, and flight speed), there were fewer age-group differences with visual messages compared with the more conventional auditory messages. In the near future, aircraft will be equipped with data link (Kerns, 1991), in which clearances from controllers will be communicated digitally to the cockpit and displayed visually. The results of Morrow, Leirer, et al. (1994) suggest that this will tend to reduce any negative impact of aging on immediate memory for ATC messages, although data link will also affect other aspects of cognitive processing, some of which may be age sensitive. For example, the multimodal environment produced by the integration of data link with existing voice ATC communication, which would require the quick switching of attention between visual and auditory modalities, may prove more disruptive to older pilots than younger pilots (Morrow, 1996).

Age-related differences have also been reported in pilot long-term memory. For example, in the recall of block shapes (Tactual Performance Test, Halstead, 1947), older GA pilots were found to be less accurate than younger pilots (Birren & Spieth, 1962; Spieth, 1964). Older pilots (retired commercial airline pilots) were also found to be less accurate than younger pilots (a heterogeneous sample of pilots) in the interpretation (e.g., choosing a referent of a pronoun) and recall of visually presented texts describing aviation scenarios (Morrow et al., 1992). Glanzer and Glaser's (1959) study is an exception. Even with an exceptionally large sample of commercial airline and military pilots ($N \approx 544$), there was a nonsignificant correlation (.08) between pilot age and memory for simple letter–number codes. The simplicity of the task, the restricted age range (with younger older participants), and the inclusion of military pilots probably account for the lack of an age association with memory for codes.

Attention. Attention is necessary for basic flight proficiency and for avoidance of accidents. In a study of USAF accidents of F-16 fighter aircraft from 1975 through 1993, approximately 20% of pilot errors were attributed to attention factors (channelized attention, distraction, inattention; Knapp & Johnson, 1996). In addition, absence of flying appears to result in the decay of attention, monitoring, and procedure-related flight skills (Childs & Spears, 1986). Attentional abilities have also been shown to be a salient factor in the prediction of successful flight performance, at least at the level of flight training. For example, performance on a divided attention test was found to substantially correlate (.42) with the pass–fail rate of airline pilots in training (Trankell, 1959). Similarly, the correlation between divided attention performance and flight check rating in private student pilots increased as flight training progressed (Damos, 1978). Individual differences in dual-task performance (but not single-task performance) were also found between pilots of varying experience (e.g., flight instructors vs. student pilots) and were predictive of flight training success (Gopher, 1982; Gopher & Kahneman, 1971; North & Gopher, 1976).

Time-sharing ability, which can be considered a metacognitive skill, is thus clearly necessary for flight proficiency. Nevertheless, age-related differences in this ability have not always been found (Braune & Wickens, 1983a). Older pilots had a greater time-sharing decrement in processing speed than younger pilots in some dual-task conditions but not in others (e.g., Szafran, 1965a, 1969; see Table 4). In a mixed sample of pilots, time-sharing efficiency decreased in older pilots, particularly when the dual-tasks had similar processing demands (such as mental rotation–horizontal tracking; Tsang et al., 1995; Tsang & Voss, 1996). Callister et al. (1996) also found greater divided attention costs in a sample of USAF pilot candidates and older commercial pilots. It should be noted, however, that individual differences in time-sharing performance were large, with some older pilots performing as well as some younger pilots (Tsang & Voss, 1996).

Attention is also a factor in monitoring, which is an important aspect of flying, particularly in modern aircraft that are highly automated. Recent studies have shown that both pilots and nonpilots are inefficient at monitoring automated systems in the cockpit when they are simultaneously engaged in other manual flight tasks (Molloy & Parasuraman, 1996; Parasuraman, Molloy, & Singh, 1993). Because monitoring is efficient when it is the only task or when it is carried out fully manually, this "automation complacency" effect has been attributed to insufficient attention allocation (Molloy & Parasuraman, 1994). There are individual differences in the extent of this effect (Singh, Molloy, & Parasuraman, 1993), including age-group differences in nonpilots when task demands are high (Hardy, Mouloua, Molloy, Dwivedi, & Parasuraman, 1995; Vincenzi, Muldoon, & Mouloua, 1997). Given that the pace of automation in aircraft shows no sign of slowing, the importance of monitoring skills in the cockpit warrants further studies to examine whether these skills decline in older pilots (see Madigan & Tsang, 1990; Singh, Deaton, & Parasuraman, 1993, October).

Problem solving–decision making. Because modern piloting is less perceptual-motor and more cognitive, studies have examined problem solving, decision making, and related higher cognitive functions in pilots (e.g., Buch & Diehl, 1984; Jensen, 1982; Lester & Bombaci, 1984; McKinney, 1993; Wiggins & O'Hare, 1995; see Telfer, 1989, for a review). In a study of GA accidents between 1970 and 1974, Jensen and Benel (cited in Tsang & Vidulich, 1989) found that 35% of nonfatal and 52% of fatal accidents were associated with poor pilot judgment. In a cognitive analysis of accident reports, pilot goal selection errors were the most frequent kind of operator error in fatal accidents (O'Hare, Wiggins, Batt, & Morrison, 1994). More than ever before, the modern commercial aviation pilot is a "manager" (not just of other crew members but of on-board automation) who is often called upon to exercise high-level cognitive skills. Unfortunately, little research has examined individual or age-related differences in these skills in pilots. Additional studies are urgently needed to rectify this need. The evidence that does exist is for very simple, artificial tasks. For example, older GA pilots have been reported to be slower than younger pilots on the Trail Making test (Reitan, 1958), taking longer to serially connect a sequence of numbers and letters (Birren & Speith, 1962; Spieth, 1964). In the Glanzer and Glaser (1959) study, older pilots were associated, to a varying degree, with worse performance when having to remember and specify principles and relationships of new aviation-related material (e.g., code learning, −.11; finding relationships, −.28; mechanical principles, −.12; and orientation to new equipment, −.20). However, in the same study, there were no significant correlations between pilot age and quantitative problem solving tasks (e.g., mathematical reasoning, −.04; numerical operations, .08; and numerical approximation, −.01) or simple verbal processing (e.g., reading comprehension, −.10). There was also no significant age-group difference in a mixed sample of pilots in performance on the Raven Advanced Progressive Matrices, a test that requires visuospatial reasoning (Tsang et al., 1995).

The Role of Expertise

Given that pilots are a highly trained group of individuals, the relationship between expertise and basic cognitive functioning also needs examination. Expert performance is characterized by the acquisition and automatization of skills (Ericsson & Charness, 1994). These skills include a qualitative change in skilled memory where information is stored and indexed in long-term memory in a way that enables quick access into working memory (Ericsson & Kintsch, 1995; Woltz, 1988). Experts also show an enhanced ability to anticipate relevant future events. These skills are domain specific and may allow the expert to circumvent normal limits in basic cognitive processing, facilitating performance in their domain of expertise.

Outside the domain of expertise, such automatized expert skills may not improve performance on basic cognitive tasks and are not always available to declarative memory. For example, when comparing younger and older pilots and nonpilots on an ATC communication type of task, Morrow, Leirer, et al. (1994) found that expertise (pilot experience) eliminated age-group differences in reading back heading commands but did not reduce age-group differences in less aviation-related tasks such as a word test and the WAIS–R Block Design test. Wiggins and O'Hare (1995) found that in GA pilots, general problem-solving ability was predictive of weather-related decision-making ability in novice flyers but not in more experienced pilots. This finding suggests that more experienced pilots go beyond general problem-solving skills when making decisions in specific flight situations.

Research examining the moderating effect of experience in older adults (e.g., Salthouse, 1991a; Salthouse & Mitchell, 1990) has shown that work experience does not prevent age-related decline in basic cognitive processing ability (Salthouse, 1990a, 1994a). Given that there are significant differences in basic cognitive abilities between younger and older adults in the general population, particularly in processing speed and in working memory, one would predict that such differences should also be found between younger and older pilots. The studies reviewed in the previous four sections generally support this proposition, a conclusion that was also reached in previous reviews (Hyland et al., 1994; Tsang, 1992).

We further tested this prediction with an analysis of RT data reported in previous studies. As shown in Figure 2, mean RT for older pilots in an experimental condition was plotted as a function of mean RT for younger pilots in that same condition in a so-called Brinley plot (Cerella, 1994). There were 53 conditions across a variety of tasks, pilot types, and ages from all the studies reviewed in this article that provided mean RT data (Callister et al., 1996; Lassiter et al., 1996; McFarland et al., 1939; Spieth, 1964; Szafran, 1965a, 1966a; Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994; Tsang et al., 1995; Yesavage et al., 1994). As Figure 2 shows, the resulting plot is highly linear (r = .99), with a slope greater than one (b = 1.46). This function is similar to old–young Brinley plots with nonpilots (e.g., Hartley, 1992). At a global level, therefore, older pilots exhibit cognitive slowing to the same extent as older adults in general.

The experience or expertise of pilots does not appear to prevent or alter the pattern of age-related slowing in cognitive processing speed that is typically observed in older nonpilots. The same appears to be true for other basic cognitive functions, although Tsang et al. (1995) and Lassiter et al. (1996) found that pilot experience did attenuate some of the age-related decline in a metacognitive skill, time-sharing proficiency. The implications of these studies are considered later, but for now the general conclusion is that flight experience does not greatly affect age-related decline in basic cognitive abilities.

This conclusion holds even though age and flight experience were confounded in most of these studies (an exception being Lassiter et al., 1996). Such a confound primarily affects the interpretation of the finding of equivalent levels of cognitive ability in young and older pilots. In this case, it could be argued that the lack of a normal age effect could be attributed to the greater experience of older pilots. The confound is less problematic if older pilots are found to

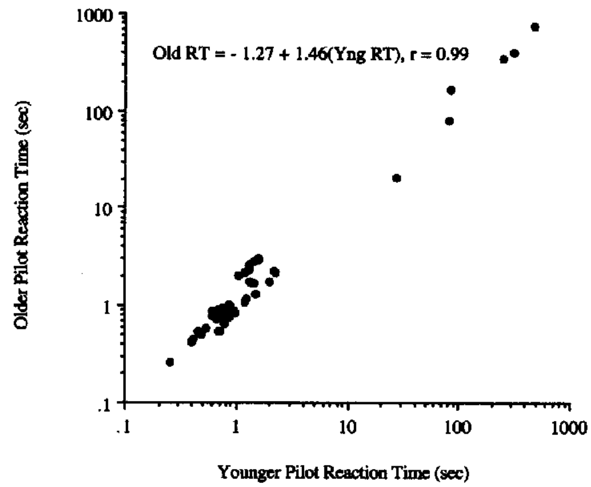

Figure 2. Older pilot mean response latencies plotted as a function of younger (Yng) pilot mean response latencies (in seconds). Digit Symbol scores (Tsang et al., 1995; Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994; Yesavage et al., 1994), which are the mean number of test items completed in 90 s, were converted to response latency scores: the mean time to complete each item (90 s per mean number of completed items). In studies with more than one age group (e.g., McFarland et al., 1939; Tsang et al., 1995), the youngest and oldest groups were used for the plot. Data used from the Lassiter et al. (1996) study included the younger, less experienced pilots and the older, more experienced pilots (to more strongly test the effects of expertise). RT = reaction time.

exhibit lower levels of cognitive functioning than young pilots. In this case, it could be argued that the age-related effect would, if anything, be greater in older pilots with the same lower levels of flight experience as young pilots. The argument is similar to the one that states if age-related differences are found for a sample of highly educated adults with above-average intelligence (as in most cognitive aging studies), then they are also likely for lower ability older adults who are more representative of the general population.

Although flight experience does not reduce age-related decline in basic cognitive functioning as measured in laboratory tasks, the question is, are these the same cognitive skills that pilots use in flying? The issue is explored in later sections of this article where we relate cognition and flight performance in older pilots. First, however, we discuss studies of flight performance in young and older pilots.

Pilot Flight Performance and Aging

Flight performance studies were grouped into two broad categories: simulated flight and actual flight. Flight simulation provides a highly controlled situation where pilot performance can be sensitively assessed in a number of situations and with a number of variables of interest (e.g., simulated weather conditions, age, drugs, etc.). Actual flight, on the other hand, provides a less sensitive but more realistic measure of pilot performance, and it includes such measures as accident rate, incident rate, and flight parameter violations.

Simulated Flight

A recent series of experiments by Morrow and his colleagues investigated age-related differences in the flight simulation performance of heterogeneous pilot samples. These experiments used a Frasca 141 simulator (Frasca International, Inc., Urbana, IL), which is characteristic of a small single-engine aircraft. The investigators were interested in the effects of aging (in addition to other variables) on various components and stages of flight performance. These included primary flight tasks, such as controlling flight path direction and altitude, and secondary flight tasks, such as ATC communication. Primary flight performance was based on deviations from an ideal flight path and was calculated for flight segments such as take-off, slow flight, descent to landing, landing, and so on. In an initial experiment, Leirer, Yesavage, and Morrow (1989) found an age-group difference in overall primary flight performance, with flight path deviations larger in older pilots (mean age = 37 years) compared with younger pilots (mean age = 26 years), with age accounting for 27% of performance variance. This finding is surprising considering the limited age range examined. Performance proficiency in both younger and older pilots was not associated with particular flight segments, and alcohol (.04% and .1% blood alcohol level) was found to impair overall performance more in older pilots than in younger pilots (Morrow, Leirer, & Yesavage, 1990; Morrow, Leirer, Yesavage, & Tinklenberg, 1991).

But subsequent studies by the same group (with mean age of the older pilot groups equal to or greater than that of the Leirer et al., 1989, study) did not find pilot age-group differences in similar measures of primary flight performance (Morrow et al., 1990; Morrow, Yesavage, Leirer, Dolhert, Taylor, & Tinklenberg, 1993; Morrow, Yesavage, Leirer, & Tinklenberg, 1993; Taylor, Dolhert, et al., 1994; Yesavage et al., 1994). Older pilots did appear to have more difficulty detecting concurrently during flight either an obstructing target in the flight path or a malfunctioning engine indicator (Morrow, Yesavage, Leirer, & Tinklenberg, 1993), and the perceived workload was sometimes greater in older pilots compared with younger pilots (Morrow et al., 1991; but see Morrow, Yesavage, Leirer, & Tinklenberg, 1993). Although there was no pilot age-group difference in primary flight performance, perhaps older pilots were closer to processing capacity or the limits of their ability (as suggested by higher perceived workload) and had exceeded this capacity with performance of the secondary detection tasks (and ATC communication as well,which will be discussed shortly). In a study presented by Hyland (1993), B727-rated pilots (mean age = 53 years, range = 41–70 years) flew a flight simulator under three workload conditions (low–routine, moderate, and high–emergency). It is interesting to note that age did not correlate with a quantitative measure (flight path deviations) of flight performance but did correlate with rater's subjective assessment of flight performance. It is difficult to reconcile differences between quantitative measures and subjective ratings of flight performance. There may be factors in flight performance that are not accounted for in objective flight path deviation measures but that are assessed by experienced raters. On the other hand, rater assessment may include bias against older pilots (see Finkelstein, Burke, & Raju, 1995, for a discussion and analysis of age discrimination in the rating of simulated work performance). Nevertheless, taking into account the present flight simulation data, age-related differences appear to be minimal in primary flight performance, at least for mean ages ranging from 37 to 60 years.

Contrary to most of the findings in primary flight performance is the evidence of age-related differences in pilot ATC communication. In these studies, pilots were given a series of simulated ATC messages (including heading, altitude, radio frequency, and transponder code commands) during various flight segments and were required to acknowledge and read back each message. Older pilots were reported to be less accurate than younger pilots in reading back radio frequency and transponder commands (Morrow, Yesavage, Leirer, & Tinklenberg, 1993; Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994). Alcohol has also been shown to negatively affect ATC communication (in flight simulation), supporting the hypothesis that tasks lower in the "aviate, navigate, and communicate" hierarchy would be dropped when processing capacity of the pilot is exceeded (Smith & Harris, 1994). Because ATC communication was performed during primary flight tasks, perhaps processing resource limits were exceeded earlier in older pilots. Older pilots were also more impaired by alcohol in reading back frequency and transponder commands (Morrow et al., 1990; however, see Morrow, Yesavage, Leirer, Dolhert, et al., 1993). However, contrary to a processing resource explanation, older pilots were not differentially affected by message length or speech rate (Taylor, Yesavage, et al., 1994), which is surprising given the decline in fundamental speech perception functioning in older adults (see Working Group on Speech Understanding and Aging, 1988). Furthermore, age-group differences in ATC communication were not reduced by practice (Morrow, Yesavage, Leirer, & Tinklenberg, 1993).

Older pilots also apparently had more difficulty in the execution of ATC commands. For example, when assigned a new flight course, older pilots (mean age approximately 40 years) were less accurate than younger pilots in changing direction to the new course (Morrow et al., 1990; Morrow, Yesavage, Leirer, Tinklenberg, 1993). In addition, alcohol impaired older pilots more than younger pilots in message execution (Morrow et al., 1990), and older pilots also made more "severe" course heading errors (deviations greater than 10 degrees) than younger pilots (Morrow et al., 1990). Because there were no differences in routine flight performance alone, the age-group differences in controller message execution were interpreted as due to communication and working memory difficulties. In fact, there is evidence that aviation mishaps are more often due to miscommunication than perceptual-motor difficulty (Grayson & Billings, 1981). And because of the apparent age-group differences in pilot ATC communication (at least represented by these flight simulation studies with GA pilots), changes in ATC procedures and design, including the impact of data link, have recently been suggested (Morrow, 1996). In general, these results showing older pilots having more difficulty with ATC communication and execution are compatible with the findings of Braune and Wickens (1983b). They found that an age-sensitive battery of five tasks (Sternberg Memory Search, compensatory tracking, dichotic listening, maze tracing, and hidden figures), their "Functional Age Battery," accounted for a significant portion of performance variance in ATC communication but not in the primary flight task.

Actual Flight

Simulator studies allow for an assessment of factors associated with flight proficiency, but measures of actual flight performance, including incidents, violations, and accident rates, can be viewed as the ultimate measure of pilot performance. Do older pilots have more accidents than younger pilots? When considering the relationship between age and flight accident rate, such factors as pilot type (e.g., military, commercial, GA), flight experience (e.g., total and recent flight hours), aircraft type, frequency of take-offs and landings, and so on must clearly be taken into account. These factors can confound conclusions about age and flight accident rate, and if they are not controlled for, they will produce inconsistent results (see Hyland et al., 1994; Li, 1994, for discussion). Probably because of convenience, many accident rate studies categorize pilots by medical certification. A Class I medical certificate requires an examination every 6 months and is the most restrictive, and it includes air transport pilots such as commercial airline pilots. A Class II certificate is updated once a year and includes commercial pilots such as air–taxi pilots and flight instructors. A Class III requires an examination every 2 years and is the least restrictive medical certification and includes GA pilots.

A number of studies reported that flight accident rate increased with age, although statistical analyses were often not conducted. Golaszewski (1983) analyzed accident data for Class I, II, and III pilots from the National Transportation Safety Board (NTSB) accident records database and the FAA Comprehensive Airman Information System (CAIS) medical certification database. For first and second class pilots (combined) with 101 to 5,000 total flight hours, accident rate was greater in older pilots compared with younger pilots. For Class III pilots, when recent flight hours were under 50, accident rate increased with age. But when recent flight hours were over 50, accident rate decreased with age. Mortimer (1991) examined GA accidents during the years 1985 and 1986 and found that private pilots over 60 years old had accident rates that were at least twice as great as the accident rates of younger pilots. Compatible results were found by Booze (1977), who reported that GA accident rates during 1974 increased as a function of age, from pilots less than 20 years old to pilots 70 years and older. In another report (Office of Technology Assessment, 1990), accident rates were examined in a combined sample of Class I and Class II pilots. For pilots with over 1,000 hr total flight experience, accident rate decreased until age 60, then nearly doubled for pilots between 60 and 69 years old. Accident rate increased after age 39 in pilots with 501 to 1,000 hr total flight experience, after age 49 in pilots with 1,001 to 5,000 hr, and after age 59 in pilots with over 5,000 hr.

In a study on Russian pilots, flight parameter violations (e.g., take-off speed low while wing flaps retracted) made available from aircraft data recorders were analyzed (Yakimovich, Strongin, Govorushenko, Schroeder, & Kay, 1994). Age correlated significantly with flight parameter violations (.45). Unfortunately, the aspect of flight violation that was correlated is unclear, and many details of the study are unavailable. Aging aviation studies on actual flight measures other than accident rate, such as parameter violations and flight incidents, are needed and could be useful in elucidating age-related differences in pilot performance.

Other studies found either no age-related change in accident rate, or a nonlinear relation between age and accident rate. Mohler, Bedell, Ross, and Veregge (1969) found that for private, commercial, and air transport pilots, accident rates for the year 1965 decreased systematically with age, from young (16 to 29 years) to older pilots (60 to 74 years). Guide and Gibson (1991) also found that accident rates (per 10,000 pilots) for the years 1982 to 1988 were highest for young pilots (25 to 29 years), but they found a curvilinear accident rate function: accident rate decreased with age up to pilots aged 45 to 49 years and then increased for pilots aged 50 to 59 years. However, flight exposure was not accounted for in these calculations. When Guide and Gibson examined accidents per 100,000 annual hours, no relationship between pilot age and accident rate was apparent. In an examination of accidents (and incidents) and flight violations across a variety of pilots (with Class I, II, or III medical certificates), older pilots (those above the median age of 41 years) were less likely (based on odds ratios) to experience an accident, incident, or violation than younger pilots (those below the median age; Lubner, Markowitz, & Isherwood, 1991).

A study of Class I, II, and III pilots was recently conducted by Kay et al. (1993). This study is noteworthy for its comprehensiveness and the use of statistical analysis. Accident rates were based on a consolidated database that merged the FAA CAIS, the Accident/Incident Database, the Pilot Deviation System, and the NTSB accident database. Their general finding was that for each class of pilots, accident rate decreased with age and remained relatively level for older pilots at least up to 64 years (see Figure 3). For Class I pilots between the ages of 30 and 59 years,

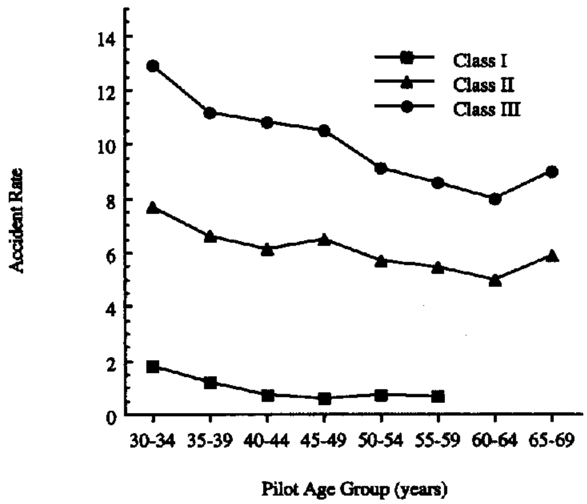

Figure 3. Accidents per 100,000 pilot flight hours for all Class I, II, and III pilots for the years 1976–1985 and 1987–1988 as a function of age group (based on figures from Kay et al., 1993).

accident rate decreased for pilots age 30 years to approximately 40 years and then remained level until age 59. When Class I pilot accident rates were examined longitudinally (as a function of birth cohort and year of accident, 1976 to 1985), accident rate decreased with age. For Class III pilots, accident rate decreased with age leveling off for older pilots, and slightly increasing after 64 years of age. It is important to note that longitudinal analysis also showed that accident rate decreased with age. Although flying routines, demands, and aircraft differ among Class I, II, and III pilots, if one interprets these medical classes as three levels of pilot expertise, then as shown in Figure 3, the benefits of expertise on flight performance (at least as indexed by accident rate) are quite large. In addition, flight hours accumulated over age appears to most benefit the pilots with the least experience (i.e., the Class III pilots).

Studies in military pilots also point to the beneficial effects of flight experience. An early series of studies on USAF pilots found that the accident rate in jet aircraft increased for pilots in their forties but mainly for those with low recent flight hours (Zeller, 1959, 1962; Zeller, Lentz, & Burke, 1963; Zeller & Moseley, 1957). In a more recent study of USAF pilots, Knapp and Johnson (1996) found that the proportion of accidents due to pilot error was greatest in 50 to 53-year-old pilots (80%), compared with younger pilots. However, flight exposure and the proportional number of active older pilots was not accounted for. Two studies looked at accident rates (the military calls them "mishaps") in U.S. Navy (USN) pilots in relation to flight experience. Borowsky (1981) showed that accident rate declined with an increase in lifetime flight experience, but that transition to a new aircraft increased risk of an accident. Later analysis of the same database with the addition of helicopter pilots produced results indicating the opposite conclusion, primarily because of the age-group differences in the helicopter pilots (Borowsky & Wall, 1983). Because these were military pilots, the age range was restricted compared with commercial and GA pilots. Although age was not directly examined, age typically correlates with flight experience (e.g., Madigan & Tsang, 1990; Tenney, 1988). Eyraud and Borowsky (1985) directly examined age and flight accidents in USN fighter, attack, and helicopter pilots. Flight records from 1977 to 1982 were categorized by age and combined with mishap records to obtain accident rates per 100,000 flight hours. The age range of the pilots was approximately 22 to 47 years. Although accident rate did not increase significantly with age, accident causal factors differed between younger and older pilots (see Figure 4). Accidents in younger pilots were more related to perceptual-motor skills, judgment errors, and inadequate situation evaluation. Examples include failure to maintain flying speed, loss of control, misjudged altitude, and failure to recognize a dangerous situation. Accidents in older pilots (38 years and older), on the other hand, were related to procedural errors, inadequate flight preparation and, to a lesser extent, regulation violations.

There are methodological differences among these studies, and as Kay et al. (1993) pointed out, there are shortcomings as well. For example, no statistical analyses were conducted on the accident data in the studies by Golaszewski (1983), Office of Technology Assessment (1990), Guide and Gibson (1991), and Mortimer (1991). The Kay et al. study included statistical analyses and is the most recent and comprehensive study. As mentioned before, they found no significant increase in accident rate in older pilots, regardless of pilot type and regardless of recent or total

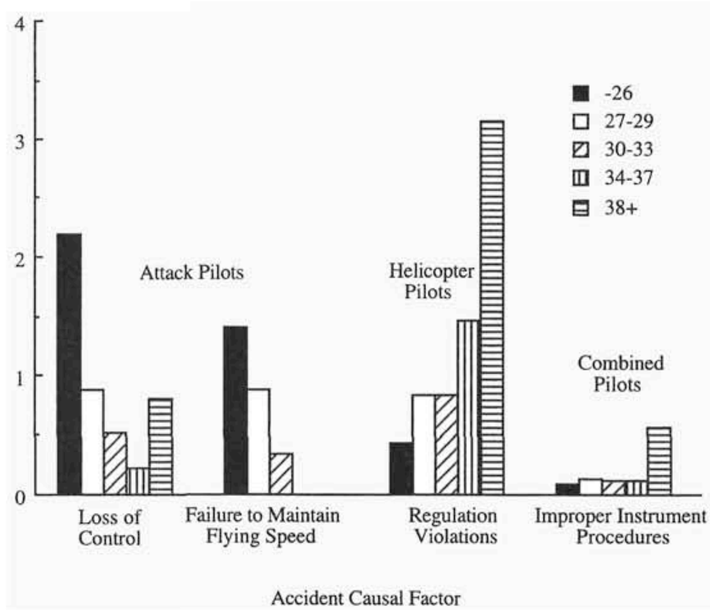

Figure 4. Accidents per 100,000 pilot flight hours for all U.S. Navy pilots for the years 1977–1982 as a function of causal factor and age group (based on data from Eyraud & Borowsky, 1985).

flight experience. Compatible with this finding, Bruckart (1992) found that, despite the increase in average pilot age from 1968 to 1987 (due to more pilots over the age of 50 and fewer young student pilots), GA accidents were 40% less than predicted (based on accident rates from 1968 to 1973). Apart from greater pilot experience, this decline in GA accidents could be due to better flight training and improved aircraft systems and design. Whatever the agent of the enhanced GA safety, it has had benefits for both younger and older pilots.

Summary of Flight Performance Studies

Primary flight performance does not differ significantly between younger and older pilots, despite a difference in basic perceptual and cognitive abilities. Almost all flight simulation studies found no age-group differences in primary flight performance measures. Age-related differences are found in voice communications. Although ATC communication is constrained by procedural expectations or a collaborative scheme (Morrow, Lee, & Rodvold, 1993; Morrow, Rodvold, & Lee, 1994), successful ATC communication performance relies fundamentally on remembering controller messages, a basic cognitive process that is highly age sensitive. Primary flight tasks (e.g., controlling the flight path, altitude, speed, etc.), on the other hand, are more complex and cognitively integrated than ATC communication, and they probably benefit more from expertise and experience, thus being more resistant to the effects of basic cognitive decline. For example, although older pilots experience a broad decline in cognitive processing speed, experience may have taught them to anticipate significant events or situations in the cockpit that might effectively compensate for their slower reactions. The benefits of skilled anticipation for memory or ATC communication are less obvious. It must be noted that these age-related ATC communication differences were found in GA pilots. A stronger test of the benefits of experience would be to examine ATC communication performance in professional or commercial pilots (e.g., Hyland, 1993).

For actual flight performance, according to the most recent and comprehensive data (Kay et al., 1993), older pilots do not appear to have significantly higher accident rates than younger pilots, at least up to 64 years of age (see Figure 3). The number of aviation accidents is also not significantly different between younger and older military pilots (who are in a more restricted age range), but the causal factors of accidents for USN pilots are more or less unique to each age group. Age did correlate with flight parameter violations in one study (Yakimovich et al., 1994), and further studies like this may be instructive. But overall, consistent age-related differences in primary flight performance, whether simulated or actual, have not been found. We discuss later whether this implies that aging does not affect flight performance or whether experience provides benefits that limit age-related decline in flight performance.

Pilot Cognition, Flight Performance, and Aging

What is the relationship between age-related differences in pilot cognition and age-related differences in flight performance? To answer this question with some satisfaction, it is necessary for one to examine cognitive proficiency and flight performance ability in the same sample of younger and older pilots. Unfortunately, this has been done in only a handful of flight simulation studies. In one group of studies (Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994; Yesavage et al., 1994), an age-related difference was found in perceptual-motor speed (Digit Symbol test). In spite of their slower processing speed, older pilots were just as proficient as younger pilots in primary flight performance measures (e.g., approach, landing, etc.). As noted previously, however, there was an age-group difference in ATC communication performance, with older pilots being less accurate than younger pilots in reading back certain ATC commands (Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994). In addition, although Digit Span score correlated with a composite measure of ATC communication performance, there was no age-group difference in average Digit Span score to account for the age-related difference in ATC communication performance (Taylor, Yesavage, et al., 1994). In a study conducted on B727-rated pilots, Hyland (1993) reported that pilot age correlated with scores on three cognitive test batteries (Wombat, Flitescript, and Cogscreen), as would be expected, and with rater's subjective assessment of flight simulation performance. However, age did not correlate with objective measures of flight simulation performance. Across these flight simulation studies in which age, cognition, and flight performance were examined in the same pilots, there was little relationship between age-related differences in cognitive proficiency and primary flight performance measures.

If we link studies of age-related differences in pilot cognition with those on age-related differences in flight performance, a clear relationship does not emerge between differences in cognition and differences in primary flight performance. Older pilots experience a variety of deficits in cognitive functioning, most pronounced in perceptual-motor and memory skills but also including attention and, to some extent, problem solving (see Table 4). However, at least with military pilots, it appears that younger pilots have more accidents related to perceptual-motor skills and judgment, whereas older pilots have more accidents related less to skill and more to factors such as regulation violations and inadequate flight preparation. And despite pilot age-related differences in cognition, according to the most recent and statistically sophisticated accident rate data (Kay et al., 1993), there are no indications that accident rate increases with age at least up to 64 years.

On the other hand, there is a relationship between laboratory memory deficits and flight simulation ATC communication errors in older pilots. Older pilots performed worse on a variety of memory tests, from traditional measures of auditory–verbal working memory such as the Digit Span (Tsang et al., 1995), to an ATC type of comprehension (Hyland, 1993), and recall task (Morrow, Leirer, et al., 1994). Compatible with these memory deficits, older GA pilots had deficits in reading back and executing certain verbal ATC commands during flight simulation (Morrow, Yesavage, Leirer, Dolhert, et al., 1993; Morrow, Yesavage, Leirer, & Tinklenberg, 1993; Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994). A caveat in this link between memory deficits and ATC communication deficits in older pilots is the lack of an age-group difference in Digit Span score in three of the studies that reported an age-group difference in ATC communication (Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994; Yesavage et al., 1994). It is also not known whether similar age-related deficits in ATC communication are found outside the simulator or in more experienced commercial or military pilots.

The Age 60 Rule

Provision 383c in Part 121 of the Federal Aviation Regulations prohibits commercial airlines from assigning pilots age 60 or older as either pilot or copilot to aircraft. The FAA put the Age 60 rule into effect in 1960 to reduce the risk of aviation accidents among older commercial airline pilots. The rationale of the FAA was based on existing studies and expert opinion that indicated two sources of an age-related threat to aviation safety: sudden inflight incapacitation, due to stroke or heart attack, and pilot skill deterioration. Because large individual differences in health status and psychological functioning exist among older persons, including pilots, the FAA determined at the time that accurate assessment and prediction of individual pilot risks was not possible with available tests and criteria. However, it was believed that the Age 60 Rule could and would be replaced quickly:

> the Agency will be able to tailor a retirement standard for each pilot instead of requiring all to quit flying at the age of 60 . . . the FAA should be well on its way toward achieving its objectives by the end of 1963 (Halaby, 1962, pp. 4 & 7).

Individualized pilot assessment pertaining to age has been more difficult than was anticipated. Research effort has gone into the development of a functional aging profile, where pilots are assessed not by chronological age but by relative skill level (Boone, 1982; Braune & Wickens, 1983a, 1983b, 1985; Gerathewohl, 1977, 1978a, 1978b; Halaby, 1962; Wickens, Braune, Stokes, & Strayer, 1985). The realization of the need for a flexible functional age index or profile to assess pilots is not new (Mohler, 1961, 1963, 1973). But over 30 years since its implementation, the Age 60 Rule still stands (and has recently been expanded to include commuter airline pilots). Challenges to the Age 60 Rule have been made since its inception (e.g., *Airline Pilots Association, International v. Quesada,* 1960; *Baker v. Federal Aviation Administration,* 1990) and arguments for its elimination are not uncommon (e.g., "Ground the Age 60 Rule," 1995; Mohler, 1981, 1985). There are, of course, factors beyond pilot ability that influence the status of the Age 60 Rule (Birren & Fisher, 1995). Extensive discussion of FAA policy and the Age 60 Rule is available elsewhere (e.g., Birren & Fisher, 1995; Dille, 1985, 1994; Salive, 1994).

Performance data from older commercial airline pilots who have high levels of experience are the most relevant for evaluating the Age 60 Rule. The relevancy of health risks in older pilots related to inflight sudden incapacitation is questionable. Since 1930, less than 1% of all aviation accidents have been due to sudden incapacitation (Froom, Benbassat, Gross, Ribak, & Lewis, 1988). But what about the FAA's other concern, that pilot skills will deteriorate in advanced age? A major foundation of pilot skills is cognitive function, which will play an increasingly important role in aeromedical standards (Mohler, 1993), but there is surprisingly little cognitive data on older commercial airline pilots (or even Class I pilots) for a research period of over 30 years. Only two studies included pure samples of commercial airline pilots (Hyland, 1993; McFarland et al., 1939). It is interesting to note that three of four studies that included commercial airline pilots in their participant samples were conducted over 20 years ago. McFarland et al. found that older pilots were slower in psychomotor performance compared with younger pilots. Hyland reported that pilot age correlated negatively with ATC comprehension (Flitescript), tracking performance (Wombat), and accuracy and speed measures on a cognitive task battery (Cogscreen). These are not many data to draw conclusions about the cognitive status of older commercial pilots. Among aviation accident reports, none have separately examined commercial airline pilots. There are a few reports in which accident rate was examined in pilots categorically similar to commercial airline pilots. Mohler et al. (1969) and Guide and Gibson (1991) examined air transport pilots. Kay et al. (1993) examined Class I pilots. In these three reports, no increase in accident rate was observed up to age 59 (the oldest pilots examined). This is compatible with Hyland's finding that age of B727-rated pilots did not correlate with flight-path deviation measures in flight simulation performance (even in the emergency or high workload condition).

The available evidence thus supports the following conclusions. In commercial airline pilots, cognitive processing speed is slower in older pilots (Hyland, 1993; McFarland et al., 1939), with a significant decline possibly beginning between 40 and 47 years of age (McFarland et al., 1939). This is similar to other kinds of older pilots (such as GA pilots) who are consistently slower than their younger counterparts on tests of cognitive speed (e.g., Digit Symbol). ATC performance may also be impaired in older commercial airline pilots, though this conclusion is based on only one correlation (Hyland, 1993). This finding would be compatible with the ATC deficits observed in other types of older pilots (Morrow, Yesavage, Leirer, Dolhert, et al., 1993; Morrow, Yesavage, Leirer, & Tinklenberg, 1993; Taylor, Dolhert, et al., 1994; Taylor, Yesavage, et al., 1994). Age does not seem to reliably influence nonverbal factors or primary measures of flight performance such as flight path deviations (as examined in flight simulators, Hyland, 1993) nor, more important, pilot accident rate (Kay et al., 1993). Thus, older commercial airline pilots (or pilots similar in flying category) experience a decline in some aspects of cognitive functioning, but this decline does not seem to translate into an increase in aviation accidents. This conclusion, which has been arrived at before (Stuck, van Gorp, Josephson, Morgenstern, & Beck, 1992), must be considered as tentative. Unfortunately, the data that are most relevant to the Age 60 Rule are only a small part of an already small body of research.

Discussion and Conclusions

The studies we have reviewed support the conclusion that older pilots show age-related decline in basic cognitive abilities—for example, reduced perceptual-motor skills, impaired memory performance, and a slowed rate of information processing. Flight experience does not alter this age-related decline in basic skills. However, there is some evidence that it may mitigate age-related decline in the metacognitive skill of time sharing.

At the same time, there are few age-related differences in pilot primary flight performance—with age-group differences most evident in the secondary task of ATC communication—and cognitive abilities are only weakly related to primary flight performance in older pilots. One possibility for the weak relationship is that the functions assessed in cognitive aging studies represent basic, domain-independent, cognitive abilities that are only one factor in determining flight performance. Higher order cognitive factors, including metacognitive skills and domain-specific knowledge, may play an equal or greater role in determining flight performance. We discuss these factors and outline a model showing how they can be linked to flight performance. First, however, we discuss some limitations of the studies we have reviewed.

Limitations of Older Pilot Studies

Nearly all of the aging studies used a simple cross-sectional design to investigate either pilot cognition or pilot flying performance. Kay et al. (1993) is an exception in being a longitudinal study. Although there are practical advantages to the cross-sectional design (e.g., data collection is considerably quicker, age groups are easily balanced, situational differences are minimal), serious interpretation difficulties arise (Baltes, 1968; Nesselroade & Labouvie, 1985; Schaie, 1965). For instance, the samples of older pilots that have been examined are, of course, those pilots who are sufficiently healthy to fly (i.e., passed the medical examination), who choose to continue flying, and who are willing to participate in a study. What about those older pilots who have been incapacitated by a flight accident or incident or who have not passed the appropriate physical? The result could be a select sample of older pilots that is not representative of older pilots in general. In addition, many of the cross-sectional studies included only two pilot age groups. If the question is whether 61-year-old pilots can operate an aircraft safely, then comparing those pilots with a group of younger pilots or to performance norms may be sufficient. However, the developmental sequence of pilot performance cannot be determined by comparing two age groups.

A general difficulty that affects the comparison of aging studies spanning several decades is the confounding of age and birth cohorts. For example, older adults born later in this century are healthier than those born at the turn of the century. Put another way, although the chronological age in 1960, (when the Age 60 Rule was introduced) of a pilot born in 1900 is the same as that today of a pilot born in 1937—both 60 years—the latter is likely to be healthier, and possibly, less prone to age-related cognitive decline. This can make comparison of studies conducted in the 1960s and 1990s difficult. Fortunately, the most recent study of pilot age and accident rate, by Kay et al. (1993), is also the most comprehensive, and it can stand on its own without need for comparison with older studies. A reason to question the Age 60 Rule, however, is that it is based on older cohorts who may not have been as healthy or cognitively skilled as today's older pilots.

Most older pilot studies also confound age with flight experience. For instance, in the Tsang et al. (1995) study, average total flight hours was 6,570 for the older pilots and 3,803 for the young pilots. As mentioned previously, confounding of age and experience is not significantly problematic for interpretation of a single result if older pilot performance is lower than that of younger pilots. The difficulty lies in interpreting a single result of age equivalency, or a pattern of results such as an age-related decline in one component of performance but age constancy in another. Does equivalent performance result from the lack of an age effect or the beneficial impact of greater experience? The only way to answer the question is to examine performance in samples of young and older pilots with similar levels of flight experience. This can be hard to do in practice, but the Lassiter et al. (1996) study was an exception where younger and older pilot samples had comparable levels of experience.

Another confound is between age range of the sample and pilot type. As Table 3 shows, pilot age range (and older mean age) was typically greater in the GA pilot samples compared with the commercial or military pilot samples. Because the GA pilots also typically had less experience or flying expertise than the commercial and military pilots, age was confounded with expertise within the older pilot samples—the less experienced (i.e., GA) older pilots were on average older than the more experienced (i.e., commercial or military) older pilots.

A specific limitation of the accident report studies is a low base rate. As is evident in Figure 3, aviation accidents are rare. A low base rate prevents much variability in accident frequency across age groups. This is particularly evident in the Class I pilots of the Kay et al. (1993) study. Another important limitation is that age is confounded with flight demands. Older pilots have seniority and have the opportunity to choose easier flight paths (with regard to weather conditions, number of take-offs and landings, airport characteristics, etc.). Therefore, total or recent number of flight hours, the typical measure of pilot experience, may not be a sensitive or descriptive enough index of pilot expertise. Hyland et al. (1994) suggested that number of landings may be a better measure of pilot flying experience and should be included in aviation databases.

Aging and Pilot Performance

These limitations temper but do not alter the conclusions we have drawn on older pilot cognition and flight performance. Some of the conclusions are supported by existing theories. For other conclusions, new conceptualizations of cognition and performance may be necessary, as discussed later. With respect to previous theories, the finding that older pilots exhibit a decline in basic cognitive functions is generally consistent with four current theories of cognitive aging (fluid–crystallized intelligence, inhibition, processing resources, and cognitive slowing). The disuse theory of cognitive aging would have predicted that specific cognitive skills related to flying would be preserved in older pilots in addition to the preservation of global flying performance. This was not the case in the majority of studies.

Our conclusion on older pilot cognition is compatible with the expertise literature and the conclusion drawn by Salthouse (1994a), which states that experience should not reduce age-related decline in basic cognitive proficiency but nonetheless provides some benefit to older adults in the preservation of performance of complex real-world tasks. Salthouse (1990a) suggested several mediating mechanisms for the preservation of global functioning in experienced older adults. These include compensation, where gains in some processes compensate for losses in other processes, and accommodation, where tasks are chosen or performed in a way so as to reduce the costs of processing deficits. There is also elimination, where proficiency in relevant skills gradually replace impaired processes, and compilation, where higher order skills, after they are developed (or compiled), become autonomous of further age-related decline in the basic underlying processes.

Although flight experience does not reduce age-related differences in basic cognitive processes, age-related differences in time-sharing ability are reduced in experienced older pilots (Lassiter et al., 1996; Tsang et al., 1995). Two cognitive aging theories, fluid–crystallized intelligence and processing resources, include a possible role for expertise in mediating age differences. Of these, resource theory is more compatible with this finding, which suggests that experience may mitigate aging of some metacognitive skills, such as time sharing. This result is also meaningful when considered together with the weak relationship between age-related differences in basic cognitive proficiency and pilot flight performance (and the generally low predictive validity of laboratory cognitive measures to flight performance, e.g., Damos, 1993, 1996). We conclude that the weak correlations arise not because cognition is unrelated to flight performance, but because the standard cognitive tests are insufficient to capture the complexity and dynamism of the cognitive skills involved in flying an aircraft. Time-sharing ability is only the simplest of the higher order or metacognitive skills that need to be considered in relationship to flight performance. We discuss these factors and provide a model to show how they can be linked to flight performance in young and older pilots.

Higher Order Cognitive Factors

We suggest that a fruitful approach, in addition to the traditional measures of cognition (working memory capacity, processing speed, etc.) and of pilot flight performance (simulator flight path deviations, ATC recall accuracy, accident rate, etc.), is to include higher order factors that tap into the knowledge structures and cognitive strategies of pilots. These are, among others, the conceptually overlapping areas of (a) mental workload and workload management, and (b) mental models and situation awareness. As is the case with performance in many complex, real-world tasks, many variables contribute to pilot performance in the cockpit. These variables may not be captured in the traditional laboratory cognitive tasks, nor are they adequately accounted for in the theories of cognitive aging discussed earlier.

Mental workload and workload management. The study of mental workload has occupied a prominent position in human factors research and practice over the past 2 decades (Huey & Wickens, 1993; Moray, 1979; Hancock & Meshkati, 1988; Warm, Dember, & Hancock, 1996; Wickens, 1992). Workload refers to the load associated with the mental (including cognitive and affective) processes of the pilot, and it has been variously conceived as: the objective task demands imposed on the pilot; the mental effort the pilot exerts to meet these demands; pilot performance; pilot physiological state; or the pilot's subjective perception of expended effort. Many definitions assume that mental workload is an intervening construct that reflects the relationship between the task demands imposed on the pilot and the capabilities of the pilot to meet those demands. Task load drives workload (Hancock, Williams, Manning, & Miyake, 1995), but workload is also mediated by the pilot's response to the load and by his or her skill level, task management strategies, and other individual characteristics such as processing resource capacity.

Processing resource theory provides the theoretical basis for workload assessment. Given that resource theory has also been examined in mainstream cognitive aging studies, it would seem appropriate to explore extensions in mental workload theory. A specific variant, multiple-resource theory (Wickens, 1984) has been examined in older pilot studies (Tsang et al., 1995). It is also instructive that the exception to the conclusion that experience does not reduce age-related cognitive decline in pilots involves time sharing, which is a component of workload and a metacognitive skill that may be particularly predictive of flight performance.

Although numerous studies have examined mental workload in pilots (see Gawron, Schiflett, & Miller, 1989; Wierwille, 1979; Williges & Wierwille, 1979, for reviews), there has been little such research devoted to age-related differences. Two flight simulation studies with younger and older age groups included a single subjective measure of mental workload with mixed results (Morrow, Yesavage, Leirer, & Tinklenberg, 1993; Morrow et al., 1991). A more promising study of mental workload was conducted by Lassiter and colleagues (1996). Their preliminary report indicates that mental workload (as measured by accuracy score on a secondary Sternberg memory task) in GA pilots while flying a flight simulator was greater in the older pilots (mean age = 55 years) compared with the younger pilots (mean age = 32 years). As discussed previously, they also found that greater flying experience reduced mental workload for both younger and older pilots (as per RT) and even mitigated (though not entirely) the effects of age in the older pilots (on response accuracy). Additional studies of this type are warranted in which a wider range of workload measures are used, including assessment of workload management strategies. For example, Tsang et al. (1995) found that pilot expertise reduced not only time-sharing decrements in older adults but also age-related deficits in resource allocation control (across a variety of dual-task priorities).

One might ask, why bother with workload assessment, given that age-related differences in pilot performance have been examined? The reason is that although performance is often correlated with workload, performance can also be dissociated from workload. For example, in a study of nonpilots, although no age-group differences were found on a Brown–Peterson memory task using simulated ATC pilot communications, older adults reported higher subjective workload levels (on the NASA-TLX [task load index] rating scale) than did younger adults (Fox et al., 1995). Would this hold for experienced older pilots as well? A high level of performance, if achieved at the cost of a sustained, very high workload, may also hide impending performance breakdown. Because workload is a state experienced by the pilot, the characteristics of this state (e.g., how much, which is related to processing resource capacity; what kind, does it involve inhibitory processes?; and how long workload has been experienced) can influence pilot functioning in a way that cannot be ascertained simply by sampling the pilot's performance. Thus, although age-related differences in flying performance are minimal, there may be differences in the level or type of mental workload required between young and older pilots. Although such differences may not be important during routine flight operations, they may pose a risk in especially high taskload situations (such as an unusual emergency or the failure of a new, unfamiliar system).

It would seem important to evaluate this potential by measuring workload in studies of aging and flight performance. Four main classes of measurement procedures have been used: primary task, secondary task, physiological, and subjective measures (Hancock & Meshkati, 1988; Wickens, 1992). In addition, modeling, or predictive workload assessment, has also been proposed (North & Riley, 1989; Sarno & Wickens, 1995). Assessment procedures that have been used with pilots include subjective assessments such as rating scales (Hart & Staveland, 1988), task analytic evaluations such as models based on task and time components and dual/multiple task performance (North & Riley, 1989), and primary task or secondary performance with single or multiple measures (Wickens, 1992). Physiological measures are often used in conjunction with behavioral measures of mental workload and include the electroencephalograph (Sterman & Mann, 1995), event-related potentials (Parasuraman, 1990), heart rate and variability (Jorna, 1993), electrooculograph (Morris, 1985), and others (see Kramer, 1991, for a review). Some of these physiological measures have been shown to be sensitive and relatively noninvasive in aviation situations (e.g., Roscoe, 1992; G. F. Wilson, Fullenkamp, & Davis, 1994), making them ideal candidates for pilot mental workload assessment.

Mental models. Experience in performing a complex, real-world task over a period of years results in the development of knowledge structures and the availability of cognitive strategies that directly influence performance. For example, Rowe, Cooke, Hall, and Halgren (1996) found that various (but not all) measures of systems knowledge (e.g., relatedness ratings of system components) were highly predictive of avionics troubleshooting performance. Such knowledge is typically thought to be encapsulated in a mental model. Although there is disagreement about the precise definition of a mental model (J. R. Wilson & Rutherford, 1989), a general description is

> a representation formed by a user of a system and/or task, based on previous experience as well as current observations, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance (p. 619).

Specifying a pilot's mental model is a complex undertaking, but it may be necessary for further understanding individual differences in pilot performance.

A mental model represents a knowledge structure that changes relatively slowly over time. Situation awareness is a more dynamic concept similar to the concept of mental model, although there are also some distinctions (see Gilson, 1995). According to one definition, "Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995b, p. 36). Situation awareness is thought to be a salient causal factor in aviation accidents, particularly those involving highly automated aircraft (Endsley, 1996). For example, in the Knapp and Johnson (1996) study of accidents in USAF F-16 pilots, 9% of pilot errors were typified as "loss of situational awareness" (p. 781). In a recent study of aviation incidents reported in the voluntary Aviation Safety Reporting System under the topic "situational awareness" (Jones & Endsley, 1996), failure to monitor or observe data was the most common error (about 35% of all situation awareness errors). As noted earlier, experimental studies have also shown that monitoring of automated systems in the cockpit can be poor under conditions of high automation reliability and high pilot workload (Parasuraman et al., 1993). Other contributing factors identified by Jones and Endsley included incomplete mental models and misperceptions.

One contribution of the situation awareness concept is that it links attention and monitoring skills—critical components of flight performance—to other cognitive concepts and structures such as working memory and mental models. In addition, the advantage of a comprehensive, albeit complex, concept like situation awareness is that it places many aspects of pilot performance within a unified theoretical framework. Because situation awareness skills and errors play a significant role in pilot flight performance, potential age-group differences in situation awareness are worthy to investigate. Certain elements of situation awareness may be differentially sensitive to the effects of aging and flight experience.

Although the assessment of mental models and situation awareness is more time consuming and difficult than the standard behavioral or performance analysis, both of these higher order factors can provide a rich source of information on pilot performance, including individual and age-group differences. Endsley (1995a) discussed the different possible techniques in assessing situation awareness and provided sample data from two flight simulation studies using a query technique.

A Model of Pilot Performance

These higher order, domain-dependent factors—mental workload and workload management, mental models, and situation awareness—interact with the basic, domain-independent cognitive abilities discussed earlier to influence flight performance. (There are also other factors, such as personality, e.g., Hormann & Maschke, 1996, social skills, and fatigue, but their consideration is beyond the scope of this article.)

A qualitative model of pilot performance is presented that outlines the contributing factors (see Figure 5). This model is based on the data reviewed in this article, areas emphasized for future research, and previous models (e.g., Hyland et al., 1994). According to this model, pilot flight performance is the product of domain-independent skills (basic cognitive abilities) and, to a greater extent, domain-dependent knowledge. Most of the factors of the model are dynamic. Skills and knowledge are modulated by pilot characteristics and pilot stressors. Some pilot characteristics and stressors change slowly (age or age-related physiological changes) and some change relatively rapidly (e.g., flight conditions, mental workload). Some are relatively stable (such as personality), and some have the potential to change (such as expertise).

In general, the structure and relations of task knowledge, skill, and performance change in a more permanent way as a function of expertise and age and in a more transient fashion due to pilot stressors. Pilot characteristics have an impact on domain-independent skills, mostly in the form of an age-related decline in these skills, which is variously accounted for by cognitive aging theories. For example, older pilot processing speed is slower than younger pilot processing speed by a constant multiple of about 1.46 (see Figure 2). Pilot characteristics are also related to domain-dependent knowledge in the sense that

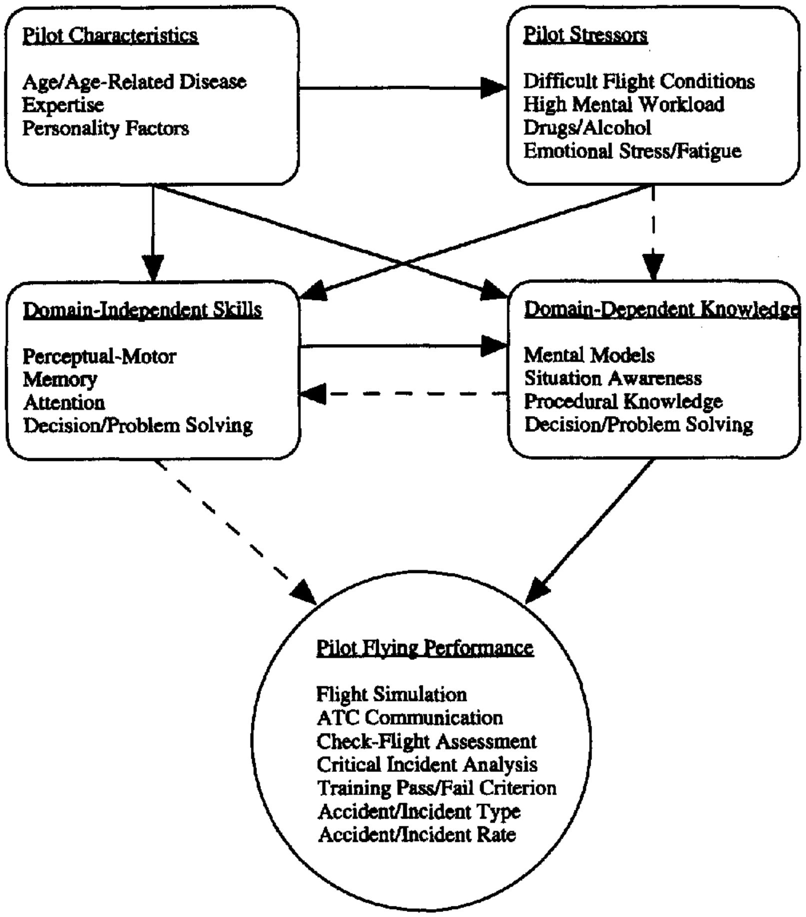

Figure 5. A model of pilot performance. Arrows imply a causal factor or a correlation. A dotted line implies a weaker connection. ATC = air traffic control.

expertise (which is the result of extended and focused experience or training) is positively correlated with task-related knowledge. Individual differences, such as in time-sharing ability (Tsang and Voss, 1996), are also an important factor in the assessment of pilot characteristics on pilot performance. Potentially large performance differences in older pilots is one reason for the inadequacy of the Age 60 Rule.

What has not been examined in pilots is whether domain-dependent knowledge remains immune to age-related decline in basic cognitive abilities—most cognitive aging theories do not explicitly address this issue (but see Salthouse, 1994a). Pilot stressors are proposed to have a greater detrimental effect on domain-independent skills (e.g., reducing working memory capacity) than on domain-dependent knowledge, and pilot stressors are modulated in turn by pilot characteristics. For example, alcohol has been shown to have a greater effect on older pilots compared with younger pilots during flight simulation. One set of problems that needs to be further addressed is the interaction of age and expertise effects on mental workload.

According to this model, domain-independent skills are necessary (but not sufficient) for the production of domain-dependent knowledge. Inversely, task knowledge has little impact on domain-independent skills. However, Ericsson and Lehmann (1996) reported that cognitive and perceptual-motor skills are improved in expert or task-dependent situations. Some cognitive abilities, for example, decision making/problem solving, may be considered to exist both as general and domain-specific skills (see Figure 5). Supportive of this idea, Wiggins and O'Hare (1995) found that general problem solving was predictive of weather-related decision making in novice pilots but not in more experienced pilots. Furthermore, although many attention skills are domain-independent, time sharing can be considered as more metacognitive or higher order in nature.

A final aspect of the model concerns comprehensive assessment of flight performance. Pilot flight performance can be measured in a variety of ways. However, there is a limit to the meaningfulness of a single measure—each measure indexes a different aspect of flight performance. As has been done with basic cognitive skills (e.g., factorial analyses), more complex analyses of pilot flying performance measures may be necessary to gain real insight into valid performance criteria and to gauge age-related changes in pilot flight proficiency. In general, pilots can be assessed at any level in this model to elucidate the complex factors producing pilot performance. Much of the laboratory aging–aviation research has focused on age-related differences in domain-independent skills. The next step is to examine higher order age-related differences in domain-dependent knowledge and to link these with pilot flight performance.

In conclusion, the point we would like to make is not that the well-known laboratory measures of cognitive proficiency are useless to aviation psychology and aging, but that there may be important age-related differences in pilot performance (not necessarily negative differences) and to discover them will require going beyond the typical measures of cognitive skill and flight performance. There may be age-related differences in pilot knowledge structure. Older pilots may use a different or unique set of expertise-related skills or strategies to offset age-related disadvantages. There may be unique mental workload characteristics of younger and older pilots that influence performance potential. These possibilities need to be directly examined.

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The 1997 Research Awards in Experimental Psychology

The awards program of the Division of Experimental Psychology of the American Psychological Association recognizes work by new investigators in all areas of experimental psychology. There is a separate award named for each of the five *JEP*s, and each year an outstanding young investigator is selected for each award. The selection is based on the quality of that person's work and its consistency with the primary subject-matter domain of that *JEP* for which the award is named. In addition, the individual selected normally is targeted for consideration by being a recent author (single, senior, or junior) of an outstanding article that was either published or accepted for publication in that *JEP*.

Kim Kirkpatrick-Steger
New Investigator Award in Experimental Psychology
Animal Behavior Processes

Jennifer Stolz
New Investigator Award in Experimental Psychology
Human Perception and Performance

Neil Mulligan
New Investigator Award in Experimental Psychology
Learning, Memory, and Cognition

Jeffrey Andre
New Investigator Award in Experimental Psychology
Applied

Akira Miyake and Priti Shah
New Investigator Award in Experimental Psychology
General