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Cognitive Ability, Expertise, and Age Differences in Following Air-Traffic Control Instructions

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Differences in cognitive ability and domain-specific expertise may help explain age differences in pilot performance. Pilots heard air-traffic controller messages and then executed them while "flying" in a simulator. Messages varied in length and speech rate. Age was associated with lower accuracy, but the expected Age × Message Difficulty interactions were not obtained. Expertise, as indexed by pilot ratings, was associated with higher accuracy; yet expertise did not reduce age differences in accuracy. The effect of age on communication task accuracy was largely explainable as an age-associated decrease in working memory span, which in turn was explainable as decreases in both speed and interference control. Results are discussed within frameworks of deliberate practice and cognitive mediation of age differences.

How well do theoretical models of cognitive aging explain age-related differences in performance of real-world tasks? Do age-related reductions in the efficiency of working memory (WM) matter when the task is familiar and its execution has been honed by experience? Although a few studies of age and expertise have addressed these questions, the results have been inconsistent. In this study of pilots' executions of air-traffic controller (ATC) communications, we examined differences in aviation performance related to age and expertise, as well as the potential for expertise to moderate the effect that age has on aviation communication performance. On average, older pilots recall ATC communications less well than younger pilots (Morrow, Leirer, & Yesavage, 1990; Morrow, Yesavage, Leirer, & Tinklenberg, 1993; Taylor et al., 1994; Yesavage, Taylor, Mumenthaler, Noda, & O'Hara, 1999). However, there is some evidence that pilot expertise may reduce (or moderate) age differences in remembering ATC communications (Morrow & Leirer, 1997; Morrow, Leirer, Altieri, & Fitzsimmons, 1994), but this has not been a consistent finding (Morrow, Menard, Stine-Morrow, Teller, & Bryant, 2001). Increased understanding of aviation communication as a specialized form of listening comprehension and immediate verbal recall would not only contribute to theoretical models of cognitive aging, but this information may also point to interventions designed to improve communication procedures. In the following section, we summarize the cognitive aging literature relevant to the constructs we investigated as potential cognitive mediators of age differences in aviation communication performance. Later, we turn to the concept of expertise, its theory, and data with respect to aging and cognition.

Cognitive Mediators of Age-Related Differences in Language Comprehension and Memory

We considered three cognitive constructs that may be useful in accounting for age-related differences in aviation communication performance: (a) WM, defined as the capacity for online storage and processing of information (Baddeley & Hitch, 1974); (b) speed of processing (Salthouse, 1980); and (c) attentional control in the face of interference or distraction (Engle, Kane, & Tuholski, 1999; Hasher & Zacks, 1988). Studies of age differences in language comprehension and immediate recall have also sought to account for age differences in terms of these cognitive constructs. Typically, however, only one of these constructs was considered in a single study, which makes it difficult to develop a model that integrates these interrelated constructs. Kwong See and Ryan (1995) and Van der Linden et al. (1999) each provided much needed joint examinations of all three constructs. In the Kwong See and Ryan study, each construct considered alone was able to explain a significant portion of the age differences in reading performance. Hierarchical regression modeling of reading perfor-

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mance further revealed that, when speed and inhibition differences were entered into the model in Steps 1 and 2, the measures of WM did not add a significant amount of incremental variance to the model. On the basis of this pattern of significant predictors, Kwong See and Ryan suggested that age differences in language performance may be fundamentally mediated by processing speed and inhibitory control. Van der Linden et al. (1999) examined all three constructs as well but used structural equation modeling. Although age differences in language performance could be explained on the basis of reductions in speed, resistance to interference, and WM, the best-fit model indicated that speed and interference effects were indirect and mediated by WM. Thus, Van der Linden et al. argued that the construct of WM should retain a principal role in explanations of age-related differences. Despite their opposing views on the importance of WM, these two investigators agreed that speed of processing and control of interference each contribute significantly to individual differences in WM and agreed that explanations should not be based on speed alone to the exclusion of control of interference, or vice versa.

The present study was designed to examine the extent to which age differences in aviation communication performance can be explained in terms of WM and, in turn, by reductions in speed and interference. In addition, we systematically varied the presentation rate and number of items in ATC messages of the communication task. We predicted that age differences would be larger when ATC messages were longer or were presented at a rapid speed rate because of the increased demands on WM processes, that is, encoding, rehearsal, and response output. In the following subsections, we elaborate on the separate, yet intersecting, views on WM, processing speed, and control over interference and discuss how these abilities are relevant to appreciating age differences in aviation communication performance.

WM, Age, and Aviation Communication

Baddeley and Hitch (1974) conceptualized WM as a system whose core component is a "limited capacity work space which can be divided between storage and control processing demands" (p. 76). WM has been a focal point of models of language processing and discourse comprehension. In research examining sources of individual differences in language performance, various loaded span tasks that stress both storage and processing have been developed as measures of WM capacity. These measures have been widely used to account for individual differences in language comprehension (e.g., Baddeley, 1992; Daneman & Carpenter, 1980; Engle, Cantor, & Carullo, 1992; Just & Carpenter, 1992; Stine & Wingfield, 1990; Tun & Wingfield, 1997). Studies that have used the span or capacity approach have implicated an age-related reduction in WM capacity as a major source of age differences in language performance, for example, sentence comprehension and memory for text (Norman, Kemper, & Kynette, 1992; Norman, Kemper, Kynette, Cheung, & Anagnopoulos, 1991; Spilich, 1983; Stine, Wingfield, & Myers, 1990; Stine & Wingfield, 1990, 1987; Tun, Wingfield, & Stine, 1991). However, some studies have been less conclusive (Hartley, 1986; Light & Anderson, 1985).

In aviation, the concept of a limited WM capacity has also been used to explain why pilots sometimes misunderstand or incompletely execute ATC radio instructions (Loftus, Dark, & Williams, 1979; Morrow, Lee, & Rodvold, 1993; Morrow & Leirer, 1997; for a review, see Morrow and Rodvold 1998). A single ATC message can vary in length, from a brief clearance (e.g., "Call sign, cleared for takeoff") to a longer set of multiple actions for the pilot to take (e.g., "Call sign, turn left heading 180, intercept the Tracy 186 radial, resume the Link 4 departure, climb and maintain 5,000 feet"; see Morrow, Lee, & Rodvold, 1993). Not surprisingly, pilots more often fail to "read back" (repeat) ATC messages accurately when messages are long and contain multiple instructions (Grayson & Billings, 1981; Loftus et al., 1979; Morrow, Lee, & Rodvold, 1993).

In earlier work, we found that forward and backward digit span scores predicted how accurately pilots read back and executed ATC communications, further implicating WM capacity as a source of aviation communication errors (Taylor et al., 1994). Recently, Morrow et al. (2001) reported that ATC read-back accuracy was predicted by sentence span scores and that age differences in a composite measure of aviation communication task performance were mediated by differences in measures of fluid cognition, including sentence span. In the present study, we have included a sentence span task and a computation span task to obtain a domain-general measure of WM. We examined the extent to which age differences in aviation communication performance could be traced to differences in WM span.

Processing Speed, Age, and Aviation Communication

Age-related reductions in WM may reflect, in part, age-related reductions in the speed of processing (Kwong See & Ryan, 1995; Salthouse, 1991; Van der Linden et al., 1999). In particular, the processing-speed theory of adult age differences (Salthouse, 1996) emphasizes that elementary cognitive operations appear to slow with age, leading to pervasive effects on the WM system and fluid cognition (see also, Birren & Fisher, 1995; Kail & Salthouse, 1994; Lindenberger, Mayr, & Kliegl, 1993; Salthouse, 1985, 1991, 1996; Schaie, 1989). Processing speed could clearly affect the comprehension of spoken messages because speech is transitory and the listener must "keep up" with the speaker's speech rate. Wingfield and colleagues have consistently demonstrated that age differences in immediate recall increase as the speech rate increases (Riggs, Wingfield, & Tun, 1993; Stine, Wingfield, & Poon, 1986; Tun, 1998; Tun, Wingfield, Stine, & Mecsas, 1992; Wingfield, Poon, Lombardi, & Lowe, 1985). As suggested by Wingfield and colleagues, obtaining an Age × Speech Rate interaction is in line with the generalized slowing and speed-of-processing perspectives (Birren, 1964; Birren & Fisher, 1995; Salthouse, 1980, 1996).

In our earlier study on age differences in aviation communication performance (Taylor et al., 1994), we manipulated speech rate using digitalized speech compression methods (similar to those used by Stine,Wingfield, & Poon, 1986). Although we found that faster speech rates did reduce the accuracy of carrying out the ATC communications, we did not detect an Age × Speech Rate interaction. This may have reflected the modest sample size ($n = 30$). It may also reflect the fact that ATC communications are highly structured and contain cues that facilitate comprehension. The most expert pilots may be especially able to cope with rapid speech rates because of more experience listening to controllers, a more accurate and up-to-date mental representation of the flight, and more dexterous execution of the instructions. Thus, we tested whether there were interactions among expertise, age, and speech rate in the current study.

Control of Interference, Age, and Aviation Communication

Alternative views of age-related decline in WM invoke explanations other than speed of processing; these are based on decreased inhibitory control, increased susceptibility to interference, or both. Indeed, one view of individual differences in WM (Engle et al., 1999) is that WM capacity is essentially "the capacity for controlled, sustained attention in the face of interference or distraction" (p. 104). Interfering information can come from a variety of sources such as internal thoughts, external noise irrelevant to the task, semantically related information, and proactive interference from previously studied items. As proposed by Hasher and Zacks (1988), older adults have problems with inhibiting the effect of interfering information. These and other investigators propose several points in processing where inhibitory deficits detract from performance: There can be lessened ability to restrict goal-irrelevant information from *accessing* WM, lessened ability to *delete* information that was once relevant but is no longer appropriate, and difficulty in *restraining* prepotent responses until they can be evaluated (Hasher, Zacks, & May, 1999).

Executing ATC commands requires holding several pieces of currently relevant numeric information in WM while translating the individual pieces of information into separate motor actions. Further, pilots need to monitor their environment while executing actions. Resistance to interference that can occur between similar items in a single ATC message, the ability to delete no longer relevant information, and the ability to switch from one action to the next are all likely to predict performance in aviation tasks such as ATC command execution.

Measures analogous to the Wisconsin Card Sorting Test (Berg, 1948; Grant & Berg, 1948; Heaton, Chelune, Talley, Kay, & Curtiss, 1993) may tap the ability to control attention and responding in the face of interference. Such tasks require participants to sort multidimensional stimuli according to a rule (i.e., color, form, or number) that shifts to another rule without warning. Participants need to flexibly adopt new sorting rules, sustain attention to the currently relevant sorting rule, and restrain from responding on the basis of a rule that is no longer relevant. The CogScreen—Aeromedical Edition (CogScreen–AE; Kay, 1995), a cognitive screening battery developed for pilots, includes a test that is similar to the Wisconsin Card Sorting Test, called Shifting Attention Discovery. We computed a composite score from this test, hereafter referred to as *interference control*, to examine the extent to which age differences in WM span scores could be traced to differences in interference control scores. Data collected by Salthouse point to a substantial amount of shared variance between interference or inhibitory control and speed of processing (Salthouse, Fristoe, McGuthry, & Hambrick, 1998; Salthouse & Meinz, 1995; Salthouse, Toth, Hancock, & Woodard, 1997). Therefore, we included paper-and-pencil measures of processing speed, so that our examination of interference control as a mediator of age differences in WM span performance could accommodate Salthouse's argument that age-related cognitive slowing has widespread influences on cognition and thus should be considered before more "specific" influences (Salthouse & Meinz, 1995).

Aviation Expertise as Moderator of Age Differences in Aviation Communication

In contrast to the age-related declines believed to occur in general-purpose cognitive systems such as WM, it is generally accepted that experts have acquired domain-specific knowledge that is relatively impervious to effects of age (see reviews by Ericsson & Lehmann, 1996; Masunaga & Horn, 2001). Experts appear to have learned pattern-action routines that effectively expand the limited capacity of WM and automate response selection; they have anticipatory skills that circumvent limitations in speed of processing. The potential age-moderating effect of expertise is important in theories of cognitive development and in design of interventions that build skills or prevent disuse.

Findings on expertise and age have varied, however—particularly so for skilled memory tasks. Although some studies in this area have found age differences to be smaller among experts than among nonexperts, many other studies do not obtain this pattern (see reviews by Meinz, 2000; Morrow et al., 2001.) The age-moderating effect of expertise may be stronger in the case of perceptual and motor skills, as seen in studies of transcription typing (Bosman, 1993; Salthouse, 1984), piano playing (Krampe & Ericsson, 1996), and microbiological specimen detection (Clancy & Hoyer, 1994). Expertise also appears to moderate age differences in deductive reasoning—as demonstrated in chess (Charness, 1981a) and the game of GO (Masunaga & Horn, 2001)—as well as age differences in time-sharing performance. Lassiter, Morrow, Hinson, Miller, and Hambrick (1996), for example, reported an interaction among age, aviation experience, and workload in the accuracy of performing Sternberg-type memory tasks while flying 10-min courses that had been memorized. Tsang and Shaner (1998) reported that aviation expertise reduced age differences in some, though not all, of the time-sharing conditions studied.

In considering past inconsistent results, Morrow et al. (1994) stressed that task-domain relevance is a crucial factor determining "when expertise reduces age differences" (p. 134). More specifically, investigators need to use tasks in which the stimuli are familiar and organized and the responses are compatible with the goals of the relevant performance domain (Vicente, 1992; Vicente & Wang, 1998). However, even when investigators designed their tasks to be domain relevant, studies of skilled memory have still failed to obtain significant Expertise × Age interactions (e.g., Meinz & Salthouse, 1998; Morrow et al., 2001). Meinz (2000) pointed out that another reason for failure to obtain an interaction may be when age-related differences in performance among the inexperienced participants are small. Taken together, expertise should moderate age effects on performance when (a) the task at hand is domain relevant, and (b) domain-general, fluid cognitive abilities predict novice performance more so than they predict expert performance.

In the present study, we examined differences in the accuracy of following aviation communications according to expertise, as well as interactions involving expertise that would suggest moderating effects. The task was designed to be domain relevant and to allow use of expert knowledge. Aviation communications (e.g., navigational headings and altitudes) represent a domain-specific language that is familiar to pilots and that has been practiced in the context of flying an airplane. Student pilots and controllers are trained to follow protocols that specify the order and specific pronunciation of elements in a communication (Federal Aviation Administration [FAA] Order 7110.650 and Aeronautical Information Manual). As did Morrow et al. (1994), we presented heading, altitude, and radio frequency information according to standard aviation protocol. Similar to Morrow et al. (1994, Experiment 2; Morrow et al., 2001), ATC messages were presented auditorially, and the pilot read back the ATC communication, which is currently typical practice for the population of pilots we studied. Auditory presentation of ATC messages should increase aviation-domain relevance because most pilots receive their ATC communications via headsets. More unique to this study is that pilots executed the ATC commands in the context of "flying" a small-aircraft simulator, a factor that further enhances domain relevance.

As in Morrow et al.'s earlier studies (1994, 2001), we did not permit pilots to use a pad (which they would have available to them in real flight) for note taking. Not having access to a notepad detracts from domain relevance and also increases demands on WM. Morrow et al. (2001, 2003) argued that aviation communication while flying imposes heavy demands on WM and that note taking, which is typically used in actual flight, provides a strategy for managing these demands. As demonstrated in studies by Morrow and colleagues, when information was auditorially presented and there was no opportunity to take notes, expertise did not reduce age differences in aviation communication read-back performance. In addition to showing that note taking determined when expertise mitigated age differences, Morrow et al. (1994) showed that communication task factors—such as speed of presentation, mode of presentation, and the complexity of information—either alone or in combination, affected the extent of expertise-based mitigation. For example, slower, written presentation of ATC messages concerning four-leg routes through the air space led to complete elimination of age differences among pilots in the accuracy of reading back heading commands. Faster, auditory presentations only reduced age differences. Taken together, findings suggest that when the stimulus is transient and needs to be internally represented, demands on WM increase. Without strategies or conditions that reduce demands on WM, expertise may not fully compensate for age-related declines in fluid abilities that impact WM efficiency. In sum, we expected to observe an effect of expertise in this study, but given heavy demands on memory imposed by rapidly spoken messages and lack of opportunity to take notes, aviation expertise might reduce, but not completely eliminate, age differences in performance.

Ericsson and colleagues have argued that expertise reflects years of deliberate practice and training to improve skills more so than the sheer accumulation of experience (Ericsson & Lehmann, 1996). Expertise in this study was defined in terms of deliberate practice, specifically in terms of the FAA aviation ratings that pilots had attained and currently held. We subgrouped our sample according to three levels of expertise: *VFR only* (rated for flying under visual flight rules only); *IFR* (rated for instrument flight rules); and *CFII and/or ATP* (certified flight instructor of IFR students or rated for flying air-transport planes). VFR is the rating given to pilots when they first obtain a license; the VFR rating restricts a pilot to flying only in good visibility conditions (with a certain number of miles of visibility and distance from clouds). An IFR rating allows a pilot to fly in poorer visibility conditions using navigational instruments. Training for an IFR rating requires at least 40 hr of instrument time, during which pilots learn how to effectively use instruments and radar information to achieve precise navigation and maneuvering and learn more about ATC instructions and procedures. More advanced ratings and certificates include flight instructor certificates and the ATP rating possessed by major airline captains.

Pilots with more advanced aviation ratings may execute ATC messages more accurately for several reasons, including the following: (a) Greater familiarity with ATC clearances and more experience listening to controllers may facilitate comprehension; (b) training in precise navigation using cockpit instruments may engender a more accurate mental representation of an assigned heading and altitude, possibly as both auditory and visual representations in memory; and (c) IFR training may instill more discipline to adhere precisely to a flight path in order to avoid citations for failures to maintain assigned headings or altitudes.

Expertise as defined in terms of aviation ratings tends to be confounded with an accumulation of hours spent flying because of the minimum number of hours required to acquire each rating. Thus, most, but not necessarily all, ATP pilots will have more flight hours than VFR pilots. Furthermore, *expertise* as defined here also reflects passing practical as well as written proficiency tests. Pilots who successfully obtain an advanced rating may have better test-taking skills or a higher level of cognitive ability. Thus, it was important to examine alternative explanations for any expertise effect found in this study.

In summary, the aims of this study were to test for effects of age and expertise on aviation communication task performance, to test whether expertise moderated (reduced) age differences in communication performance, and to test whether effects of age and expertise increased as a function of faster speech rates of controllers and longer ATC messages. In addition, we performed supplementary analyses in which we addressed issues of mediators of the effects of expertise and age. Regarding expertise, we first asked, Is the effect of expertise just as easily explained by hours of flying? Second, is the effect of expertise due to selection of more cognitively capable individuals? Further, regarding age and expertise, we asked, Are age differences in aviation communication task performance explainable in terms of a decrease in domain-general WM, even as aviation expertise increases?

Method

Participants

The participants were 97 licensed civilian pilots (82 men and 15 women) between 45 and 69 years of age who were participants in an ongoing longitudinal study of age-related changes in pilot performance. At entry into the study, participants were required to be actively flying, have a current FAA medical certificate, and have at least 300 hr, but no more than 15,000 hr, of total flight time. Pilots from major air carriers were excluded because such pilots must retire at age 60 under current law, and, therefore, decline in flight simulator performance after that age could simply be explained by less opportunity to fly after retirement. Thus, we selected a group of nonairline pilots whose practice of aviation skills did not necessarily change at age 60. All participants gave written informed consent to participate and could withdraw at any time. The racial/ethnic distribution was as follows: 93 White (non-Hispanic), 2 African American, 1 Hispanic, and 1 “other” participant. The average level of education was 16.6 years ($SD = 2.0$). The data reported here were collected at the entry point into the longitudinal study, at which time each pilot performed three training flights and two test flights over a 4–6-week period. Other published data about this sample appears in works by Yesavage et al. (1999) and Taylor, O’Hara, Mumenthaler, and Yesavage (2000).

Expertise levels: Aviation ratings groups. Twenty-five participants had a VFR rating only (VFR group), and 53 had an IFR rating in addition to a VFR rating (IFR group). The remaining 19 had VFR and IFR ratings, plus more advanced aviation ratings that certified them as instructors of pilots learning IFR procedures and/or that rated them as air-transport pilots (CFII/ATP group). The majority of the CFII/ATP group (12/19) were currently employed as either full-time air transport pilots (3), part-time air transport pilots (4), or CFIIs (3) or their job duties included aircraft piloting (2). Within the IFR group, 2 of 53 were part-time CFIs, 2 were aviation analysts, and 1 had been an army aviator, whereas the remaining 48 had careers unrelated to aviation. Within the VFR group, all were recreational pilots, though 2 VFR pilots had aviation-related employment (airplane broker and aircraft mechanic). As can be seen in Table 1, the groups were similar in terms of educational level ($F < 1$).

Across the three groups, there were statistically significant differences in the total number of flight hours logged, $F(2, 94) = 24.74$, $p < .01$, such that the CFII/ATP group had more total hours of flight time than the IFR group, and the IFR group had more total hours of flight time than the VFR group (see Table 1 for *M*s and *SD*s). There were no significant differences across groups in terms of the average number of flights reportedly flown during the past 12 months, $F(2, 94) = 2.52$, $p = .09$. (Note that analyses of variance were performed on the ranked hours and flights.) Thus, total flight experience may offer an alternative explanation for aviation group differences in performance.

Age. The age distribution of the sample was as follows: ages 45–49 years ($n = 8$); ages 50–54 years ($n = 25$); ages 55–59 years ($n = 31$); ages 60–64 years ($n = 20$); and ages 65–69 years ($n = 13$). Although our sampling strategy was designed to avoid a strong confound between age and aviation experience, there were slight differences in the mean ages of the three aviation ratings groups: VFR = 56.1 years, IFR = 58.6 years, and CFII/ATP = 55.3 years (see Table 1 for *SD*s). These overall group differences in mean age were marginally significant, $F(2, 94) = 2.98$, $p = .06$. Duncan’s multiple-range test indicated that the mean age of the VFR group was not significantly different from that of the other two groups, but the IFR group was just barely significantly older than the ATP/CFII group (critical range = 3.31 years; observed range = 3.32 years). Most important, there was no systematic trend for age to increase or decrease from one aviation ratings group to the next ($r_s = -.04$). Similarly, age was not significantly correlated with either total number of flight hours logged ($r_s = .15$) or with the number of flights reportedly flown during the past 12 months ($r_s = -.18$). Age was not significantly correlated with years of education ($r = -.06$).

Cognitive ability scores. As described below, composite scores were computed from individual measures of WM span, speed, and interference control. Pilots with advanced aviation ratings did not have significantly better scores. Relations between aviation ratings and cognitive ability scores are described in detail in the Results section.

Design

During each of five simulated flights, pilots heard 16 tape-recorded ATC messages. The communication task had four levels of difficulty, with messages presented at a normal or a fast speech rate and with either three items or four items in a single ATC message. In this design, the between-subjects variables were age (a continuous variable) and expertise group

Table 1
Demographic and Cognitive Ability Measures (Mean +/− SD) for the Three Aviation Ratings Groups (N = 97)

	VFR-rated ($n = 25$)		IFR-rated ($n = 53$)		CFII or ATP-rated ($n = 19$)	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*
Demographic measures						
Age (years)	56.12	6.08	58.58	5.96	55.26[a]	4.95
Education (years)	16.48	2.22	16.79	1.83	16.21	2.39
Total no. of flight hours logged	1,199.80	1,548.00	2,029.38	1,928.46	5,515.26[b]	2,963.82
Average no. of flights/month in past year	4.87	5.08	5.92	6.25	10.93[c]	10.72
Working memory span measures						
Computational Span	6.28	1.81	5.91	1.60	6.63	1.95
Sentence Span	4.44	1.29	4.09	1.43	4.95	1.51
WAIS–R Forward Digit Span	9.60	2.40	9.87	2.49	10.53	2.34
WAIS–R Backward Digit Span	8.76	2.57	9.25	2.81	9.32	2.69
CogScreen–AE Visual Backward Digit Span (% accuracy)	82.36	17.33	85.09	15.61	88.72	17.15
Working memory span composite score (*z* score units)	−0.06	0.68	−0.06	0.75	0.25	0.72
Speed of processing measures						
Pattern Comparison (no. completed)	18.94	2.39	17.74	2.84	17.53	3.37
Digit Copying (no. completed)	50.76	7.27	49.63	8.76	47.11	9.42
Speed composite score (*z* score units)	0.24	0.71	−0.03	0.90	−0.22	1.02
Interference control measures: Shifting Attention Discovery Test						
No. of rule shifts completed	6.84	2.51	5.64	3.22	6.89	2.56
No. of failures to maintain set	2.08	1.75	2.45	1.96	1.89	1.24
Interference control composite score (*z* score units)	0.16	0.87	−0.15	1.04	0.22	0.71

Note. VFR = rated for flying under visual conditions; IFR = instrument rated, which allows a pilot to fly in clouds by using cockpit instruments to navigate; CFII or ATP = certified flight instructor of pilots in training for IFR and/or certified to fly large air-transport planes; WAIS–R = Wechsler Adult Intelligence Scale—Revised; CogScreen–AE = a cognitive screening battery developed for pilots.
[a] ATP/CFII group significantly younger than IFR group by Duncan’s multiple range test, a = .05, critical range = 3.31 years. [b] Each group significantly different from adjacent group by Duncan’s multiple range test on ranked values, $\alpha = .05$. [c] ATP/CFII group significantly different from the VFR group by Duncan’s multiple range test on ranked values, $\alpha = .05$.

(VFR, IFR, or ATP/CFII). The within-subject variables were speech rate (normal vs. fast) and message length (three-item message vs. four items). The participant's performance in the simulator was scored in terms of the accuracy of executing each instruction of an ATC message.

Aviation Measures and Equipment

Aviation communication materials. Eleven scripts, each containing 16 critical ATC messages, were used in this study. In any script, 8 of the messages contained three ATC instructions and 8 contained four. In addition, half of the messages were auditorially presented at a typical ATC speech rate (approximately 235 words per minute; wpm), whereas the other half were digitally compressed by 35% to create a "fast" speech rate of approximately 365 wpm. A three-item message instructed the pilot to fly a new heading and altitude and to change the radio contact frequency (e.g., "Cessna one four seven niner Bravo, fly heading two four zero, climb and maintain one thousand six hundred feet, contact Bay Approach on one two seven point three.") The four-item message contained similar items, plus a radar transponder code (e.g., "Squawk zero six two four"), which was inserted before the radio frequency. This presentation order follows FAA standard protocol (FAA Order 7110.650). The four message types (three-normal, three-fast, four-normal, and four-fast) occurred four times each in a 16-message script. Their order was random with the restriction that each type would occur once in a block of four messages.

The headings were drawn from a set of 26 headings ranging from 010 to 340° (all ending with a zero). There were 12 possible altitudes ranging from 0700 to 1,800 ft (213.36–548.64 m), inclusive. Radio frequencies ranged between 120.1 and 129.8 (e.g., 127.3), except that local aviation frequencies were not used. The transponder codes were octal based and contained four digits between 0210 and 0760, with the restriction that the codes would have no identical digits except for the flanking 0s. Thus, a typical three-item ATC message contained a total of six unpredictable digits, and a four-item message contained eight.

The ATC scripts were tape-recorded by a male professional air-traffic controller speaking in his normal rate and intonation. The recordings were then digitized using a Farallon Computing MacRecorder. One script was used for introducing participants to the task and was presented entirely at the normal ATC speech rate (an average of 235 wpm). For the other scripts, half of the three-instruction messages and half of the four-instruction messages were compressed 35% using the audio signal compressor provided with SoundWave 1.0 (Ryall & Durkee, 1987), to create the "fast" speech rate.

Flight simulator and equipment. The aviation communication task was presented while pilots "flew" in a Frasca 141 flight simulator (Urbana, IL). The simulator was linked to an IRIS 4D computer (Silicon Graphics, Mountain View, CA) that generated "through-the-window" graphics of the environment and collected data concerning the aircraft's position and radios. This system simulated flying a small single-engine aircraft with fixed landing gear and fixed propeller above flat terrain with surrounding mountains and clear skies. The ATC scripts were presented binaurally via speakers installed in the cockpit, with each participant adjusting the volume to his or her preferred level.

Aviation communication task. During a flight, the 16 ATC messages were presented at the rate of one message every 3 min. A flight began with the controller's takeoff clearance. The first critical ATC message was presented 3 min later, after participants had lifted off the runway and climbed to 1,200 ft (365.76 m). Participants were instructed to read back the ATC instructions of each ATC message, guessing if necessary, and then execute them in the following order: initiate the new course, change the radio frequency, and change the transponder code, if applicable. Participants flew on the new course for 3 min and then received the next ATC message, which contained new course and radio/transponder instructions. Participants were instructed that the heading changes should follow the FAA's standard turn rate of 3° per second and that altitude changes should be done safely, for example, to avoid stalls during climbs, with the aim of reaching the new assigned altitude at approximately the same time as the new heading was reached. They were also informed that they could dial in the new radio and transponder code at any point during the leg, though sooner was preferred. The 16 ATC messages were followed by two "filler" ATC messages that provided base and final leg instructions for landing. Every flight involved taking off and landing at the same airport; each flight lasted approximately 75 min.

In addition to following ATC communications during the flight, participants had to monitor all cockpit instruments, particularly the oil and manifold pressure gauges on the instrument panel, for indications of engine malfunction and had to avoid other aircraft. Engine malfunctions were simulated during 8 of the legs, and an oncoming aircraft appeared during 10 of 16 legs (each time approaching in one of four imaginary quadrants). Pilots were instructed by the examiner to immediately report engine malfunctions and to avoid air traffic by veering quickly yet safely in the direction diagonal to the path of the oncoming plane. These "emergency" situations occurred randomly, with the restriction that they not occur simultaneously with an ATC message and its execution. Pilots flew in severe turbulence throughout the flight and also encountered a 15-knot crosswind during approach and landing. The relation of age to performance on these tasks has been reported elsewhere (Yesavage et al., 1999).

Prior work has determined that execution and read-back responses strongly agree with each other (Taylor et al., 1994), and both correlate strongly with span measures of WM (Morrow et al., 2001; Taylor et al., 1994). We focused on the accuracy of execution, similar to Taylor et al. (1994), because the computer connected to the simulator automatically collects aircraft-position and radio-communication data and scores them for accuracy. A heading was scored as correct if it was within 10° of assigned value, and an altitude was correct if it was within 100 ft (30.48 m). Radio frequency and transponder codes were scored on an all-or-none basis.

Cognitive Tasks and Computation of Composite Scores

Several tests of WM, speed, and interference control were administered to achieve reliable composite measures of each construct. Table 1 lists the means (and *SD*s) of the individual tests making up the composite measures. Described below are the individual tests and the method of computing each composite score.

WM capacity: Span tasks. Five span measures were collected. First, the WAIS–R Digit Span Forward and Backward tests were administered according to the manual (Wechsler, 1981). In addition, three computerized WM span tasks were administered. The first 2, Computation Span and Sentence Span, were kindly provided by Timothy Salthouse. In the Computation Span task, the participant saw a sequence of up to nine arithmetic problems (such as $6 + 2 = ?$) and three response alternatives. As the participant answers the problems in a sequence, he or she is asked to remember the last digit of *each* problem in that sequence (2, in this example). The first trial had one arithmetic problem and one memory item. If the participant correctly recalled all the memory items on three consecutive trials, then the number of problems (and memory items) was increased by one. Computation span was scored as the largest number of digits the participant could correctly recall on at least two out of three test trials. The Sentence Span test and measurement of span was similar, except that participants answered questions about sentences, and their task was to remember the last word of each sentence in a sequence. Visual Backward Digit Span was administered as part of the CogScreen–AE battery. In this test, between three and six digits are displayed sequentially on the computer monitor, and the participant's task is to reproduce the sequences in the reverse order. The Visual Backward Digit Span score is the percent accuracy for up to eight trials.

The age-partialed intercorrelations among the WM span measures in this sample were moderate in size. (We computed age-partialed correlation coefficients for conservative indications of convergent validity.) For example, the correlation coefficient between the two Salthouse span scores was .44; between the two WAIS–R spans, it was .58. We estimate that a correlation in the range of .5–.6 is about as high as one can expect to observe in this sample because of unreliability of the individual measures. For example, the test–retest reliability coefficients for Computation Span and Sentence Span, using data from the practice and test sessions, were .42 and .62, respectively. A principle-components analysis of the five span measures yielded a single component (eigenvalue > 1) with loadings ranging between .67 and .80, which accounted for 52% of the variance. Therefore, we computed a single composite WM span score by standardizing the five scores and then averaging them together (Rushton, Brainerd, & Pressley, 1983).

Speed of processing. Pattern Comparison and Digit Copying (Salthouse, 1992b) were used to measure speed of processing. In the Pattern Comparison task, participants were asked to make same–different decisions about pairs of patterns made of connected line segments. In the Digit Copying task, participants were asked to copy digits as rapidly as possible. For each task, participants were given two 30-s trials, and the number of correct responses was scored. The test–retest correlations (Trial 1 with Trial 2) were .73 for Pattern Comparison and .92 for Digit Copying. The age-partialed correlation between Pattern Comparison and Digit Copying number correct was .52. The two scores were standardized and then averaged together to provide a composite measure of speed.

Interference control: Conceptual set shifting and maintenance. The Discovery subtest of the Shifting Attention Test, available in the CogScreen–AE (Kay, 1995), a computerized aviator assessment battery, was used in measuring the ability to maintain interference control. As in the Wisconsin Card Sorting Test, the participant's task is to use trial and error to discover which of multiple stimulus dimensions (such as object color) is currently relevant and then use that dimension as the sorting rule until feedback indicates it is no longer relevant. Figure 1 shows two sample trials. Each of the 64 test stimuli in this test is a randomly generated square

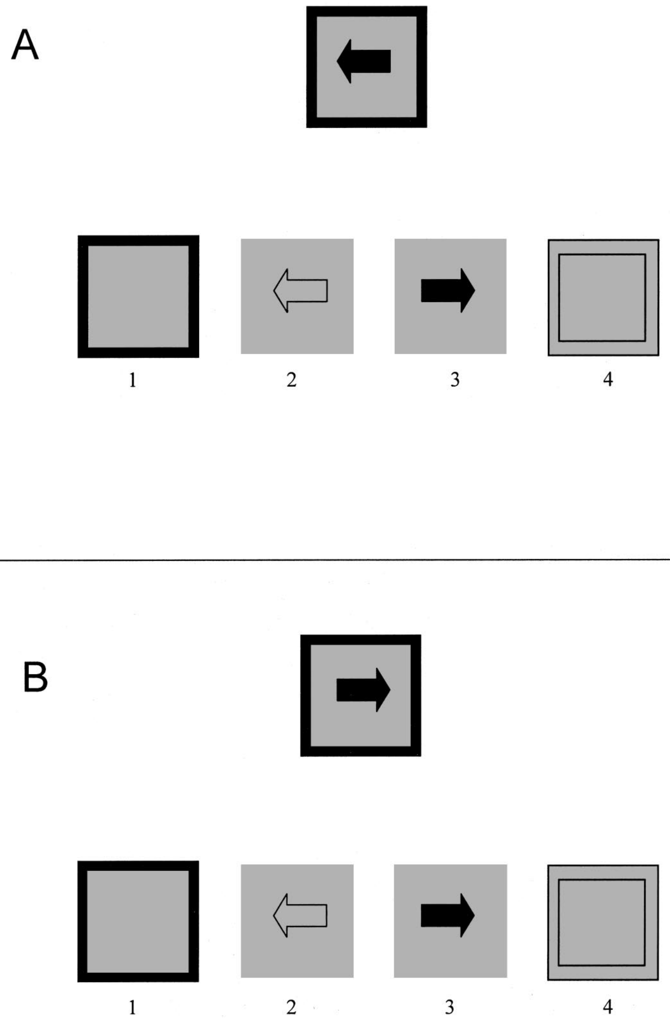

Figure 1. CogScreen–AE Discovery Test: two sample trials. A: An incongruent trial. If *border color* is the rule, the participant should point to Box 1 in the lower row. If *arrow direction* is the rule, then the participant should point to Box 2. Note that test stimulus and correct response are incongruent for arrow color. If *arrow color* is the rule, Box 3 is correct even though the test stimulus and correct response are incongruent for arrow direction. B: A congruent trial. If *border color* is the rule, the correct response is Box 1. If either *arrow direction* or *arrow color* is the current rule, then Box 3 is the correct response. For these two rules, the test stimulus and correct response are congruent in color and direction.

with a surrounding border that is either purple or yellow; inside each square is a yellow or purple arrow pointing left or right. The four possible response choices remain constant across trials. The participant's task is to touch the response box that matches the stimulus according to border color, arrow color, or arrow direction. The sorting rule changes after 4–6 consecutive correct responses, at which point the participant should attempt to discover the new rule.

In tasks such as Shifting Attention Discovery, successful performance may be supported by (a) memory and control of proactive interference, (b) attentional inhibition of irrelevant objects or stimulus features, and (c) suppression of prepotent responses. Intact memory processes would support learning a rule by retrieval of previous feedback information. Once a rule is acquired, the rule needs to be maintained in memory across consecutive trials. When a rule is no longer relevant, that particular rule should be deleted from WM and its attendant actions suppressed. For each separate rule, successful performance may involve the ability to ignore irrelevant objects and features. That is, when *border color* is the active rule, one should ignore the irrelevant internal object, that is, the arrow, of the test stimulus. When *arrow direction* or *arrow color* is the active rule, one should ignore the irrelevant feature of the arrow because there is a 50% chance of incongruency between the irrelevant feature of the test stimulus and that of the correct response. Figure 1A shows such incongruency. When *arrow color* is the active rule, there is incongruency in arrow direction, because the arrow in the test stimulus points to the left and the arrow inside the correct response box (Box 3) points to the right. When *arrow direction* is the active rule, there is incongruency in arrow color, because the arrow in the test stimulus is purple whereas the arrow in the correct response box (Box 2) is yellow. Figure 1B illustrates congruency.

The Shifting Attention Discovery task provides three "process" variables that are scored similarly but not identically to the Wisconsin Card Sorting Test. The Discovery process variables have been found in factor analysis to load on a single factor (Kay, 1995, p. 71). These are (a) number of rule shifts completed, (b) number of failures to maintain set, and (c) number of perseverative errors. A failure to maintain set is recorded when the participant errs after two consecutive correct responses. In the present sample, we found that failures to maintain set and the numbers of rule shifts completed were strongly and negatively intercorrelated (age-partialed $r = -.72$), whereas perseverative errors were not correlated with either (*r*s of .01 and −.02, respectively). Therefore, we used the first 2 variables only in computing a composite measure from this test, which we call "interference control."

Procedures

After three familiarization sessions with the flight simulator and aviation communication task, each participant performed five test flights over a 4–6-week period. They heard a different script at each session to prevent learning of the specific flight instructions. Participants did the WAIS–R Digit Span test during the third familiarization session; they practiced the Computation Span after Flight Test 1 and practiced the Sentence Span tasks after Flight Test 2. Flight Tests 1, 2, and 3 each took place in a separate 2-hr session, with typically two sessions per week. From 3 to 4 weeks later, the participant participated in a 7-hr test session that included a morning flight test, half of the cognitive test battery, a 40–60-min lunch break, an afternoon flight test, and the remaining cognitive tests. The two halves of the cognitive battery were Part 1: perceptual speed tasks, Salthouse Span tasks, and three selected reaction time tasks of the Walter Reed Performance Assessment Battery (Thorne, Genser, Sing, & Hegge, 1985); and Part 2: the entire CogScreen battery, which takes 40–60 min. The order of Parts 1 and 2 was by random assignment. Results of the Performance Assessment Battery are forthcoming.

Results

Effects of Age, Aviation Expertise, Speech Rate, and Message Length on Aviation Communication Task Performance

Table 2 summarizes aviation communication task performance in relation to age, expertise (as defined by aviation ratings), and task condition. These data were analyzed using the statistical methods described below to examine effects of age and expertise on aviation communication task performance; to determine whether expertise moderated the effect of age on communication performance; and to understand whether effects of age and expertise increased as a function of faster speech rates of the controller, longer ATC messages, or both. As a preview of our results, we note that increased age was significantly associated with lower aviation communication performance overall but that the expected Age × Task Difficulty interactions were not obtained. Increased expertise, as indexed by aviation ratings, was significantly associated with better aviation communication task performance, but expertise was not found to moderate or reduce age differences in performance.

Statistical approach. To test for main effects of age (a continuous variable), expertise (an ordinal variable), and Age × Expertise interactions, we used general linear modeling (SAS Proc GLM). Each participant's data were reduced to four dependent variables, and in all analyses, the values of age and expertise were centered (Aiken & West, 1991). The dependent variables were an overall number correct score and three orthogonal contrast scores that captured the two within-subjects factors of the design: speech rate and message length. The contrast scores were (a) the *rate contrast score*, that is, the average number of items correctly executed in the two normal rate conditions minus the average number recalled in the two fast rate conditions; (b) the *length contrast score*, that is, the average number correct for the two 3-item conditions minus the average correct for the two 4-item conditions; and (c) the *Rate × Length contrast score* (see bottom of Table 2 for equations). We used contrast scores to test the within-subjects effects of rate and length because rarely is it true that a design with four or more repeated measures per participant satisfies the compound symmetry assumption of repeated measures analysis of variance. To compute contrast scores, we first averaged participants' scores across test sessions to gain greater reliability (Rushton et al., 1983). Our previous analyses with similar data sets have not detected significant age differences in practice effects (Morrow, Yesavage, et al., 1993; Taylor et al., 1994). In addition to the contrast scores, an overall number correct score was computed, which was the participant's average accuracy across all message conditions and test sessions. Each dependent variable (rate, length, Rate × Length, and overall score) was analyzed using GLM. Each GLM tested the main effects of age and expertise and the Age × Expertise interaction.

Overall accuracy score. There were significant effects of age and expertise on the overall number correct in the aviation communication task (see *F* ratios in the upper portion of Table 3). Older pilots executed ATC messages less accurately than younger pilots on average. Pilots with more advanced aviation ratings executed ATC messages more accurately than less highly certified pilots, as hypothesized. The Age × Expertise interaction was not

Table 2

Aviation Communication Task Performance: Number of Items Correctly Executed (Mean ±SD) for the Three Aviation Ratings Groups, Split Into Two Age Groups (N = 97; Mean/Median Age = 57 Years)

	VFR-rated		IFR-rated		CFII or ATP-rated	
Condition and variable	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age ≤ 57 years						
Task conditions	*n* = 14		*n* = 24		*n* = 14	
3 items, normal speech rate	2.18	0.45	2.21	0.47	2.41	0.30
3 items, fast speech rate	2.13	0.43	2.08	0.42	2.29	0.37
4 items, normal speech rate	1.98	0.59	2.16	0.52	2.31	0.51
4 items, fast speech rate	1.81	0.45	1.87	0.47	2.00	0.49
Dependent variables						
Overall number correct	2.02	0.46	2.08	0.44	2.25	0.39
Rate contrast score	0.11	0.18	0.21	0.24	0.21	0.20
Length contrast score	0.26	0.24	0.13	0.20	0.19	0.25
Length × Rate interaction contrast score	0.06	0.13	0.08	0.17	0.09	0.14
Age > 57 years						
Task conditions	*n* = 11		*n* = 29		*n* = 5	
3 items, normal speech rate	1.79	0.35	2.00	0.37	2.12	0.33
3 items, fast speech rate	1.57	0.50	1.82	0.41	1.95	0.29
4 items, normal speech rate	1.69	0.45	1.79	0.35	1.79	0.09
4 items, fast speech rate	1.53	0.36	1.63	0.32	1.78	0.20
Dependent variables						
Overall number correct	1.64	0.38	1.81	0.33	1.91	0.21
Rate contrast score	0.19	0.21	0.16	0.17	0.09	0.09
Length contrast score	0.08	0.21	0.20	0.18	0.25	0.21
Length × Rate interaction contrast score	−0.03	0.21	−0.01	0.14	−0.08	0.08

Note. Overall number correct = participants accuracy score, averaged over all message conditions. Rate contrast score = the average number correct in the two normal (*N*) rate conditions minus the average correct in the two fast (*F*) rate conditions or [(3N + 4N)]/2 − [(3F + 4F)]/2. Length contrast score = the average number correct in the 3-item conditions minus the average correct in the 4- item conditions or [(3N + 3F)]/2 − [(4N + 4F)]/2. Rate × Length contrast score = [(4N − 4F) − (3N − 3F)]/2. VFR = rated for flying under visual conditions; IFR = instrument rated, which allows a pilot to fly in clouds using cockpit instruments to navigate; CFII or ATP = certified flight instructor of pilots in training for IFR and/or certified to fly large air-transport planes.

significant in the analysis of scores for overall number correct. Figure 2 provides a scatter plot of participants' overall accuracy scores. In this figure, three age-trend lines are superimposed on the scatter plot, one for each level of expertise, because the parameter for the expertise term was significantly greater than zero. The age-trend lines are nearly parallel because the parameter for the Age × Expertise interaction term was near zero. (The parameters fit by the general linear model are listed in the figure caption.)

Contrast scores. Analyses of the rate and length contrast scores revealed no significant effects of age or of expertise (see Table 3). That is, older pilots were not differentially affected by faster rates and longer messages; performances of more highly trained and rated pilots were not differentially superior under the more demanding task conditions of faster speech rates or longer messages. However, our experimental manipulations of speech rate and message length were clearly effective. When the speech rate was normal, the average number correct was 2.05 instructions; performance declined to 1.88 instructions in the fast speech rate condition: mean rate contrast score = 0.17 ± .20, $t(96) = 8.65$, $p < .01$. Presentation of a fourth instruction in the ATC message also resulted in less accurate execution: When a message contained three instructions, participants correctly executed an average of 2.05 instructions; accuracy declined to 1.87 instructions when ATC messages were longer: mean length contrast score = 0.18 ± .21, $t(96) = 8.32$, $p < .01$. A *t* test of the Rate × Length contrast scores also confirmed that rapid speech rates were particularly detrimental to performance when the ATC messages contained four items in comparison with when messages contained three items: mean Rate × Length contrast score = 0.032 ± .16, $t(96) = 1.97$, $p < .05$, one-tailed.

Although there were no significant effects of age or expertise in the analyses of the rate and length contrast scores, age had an unexpected influence on the magnitude of the Rate × Length contrast scores, $F(1, 93) = 6.18$, $p < .05$. As can be seen in Table 2, the Rate × Length contrast scores were slightly negative for older pilots, even though the mean score was positive. This means that older pilots appeared to be less affected by the combination of fast speech and an additional fourth command item. Negative contrast scores of the older participants could be a consequence of low values in the four-item conditions. A floor effect for many

Table 3

General Linear Model Results: Effects of Age, Expertise (Aviation Ratings), and Age × Expertise Interaction

	Source			
Dependent measure	Age	Expertise	Age × Expertise	Error
Aviation communication task	$F(1, 93)$	$F(1, 93)$	$F(1, 93)$	
Overall score	17.42**	5.63*	0.00	0.146
Length contrast score	0.21	0.62	2.72	0.441
Rate contrast score	1.08	0.16	0.99	0.388
Rate × Length contrast score	6.18*	0.16	0.07	0.025
Cognitive ability scores	$F(1, 93)$	$F(1, 93)$	$F(1, 93)$	
Working memory span composite score (*z* score units)	8.60**	1.24	0.41	0.492
Speed composite score (*z* score units)	21.27**	5.57*	2.69	0.639
Interference control composite score (*z* score units)	8.42**	0.00	0.07	0.841

* $p < .05$. ** $p < .01$.

older participants, combined with the fact that the age effect was not in the direction hypothesized, suggests a possibly spurious result.

We now turn to the supplementary analyses in which we addressed questions concerning potential mediators of the effects of age and expertise on overall accuracy of aviation communication task performance. The data were analyzed to address the following questions.

1. Regarding expertise, first, is the effect of expertise just as easily explained by hours of flying? Second, is the effect of expertise due to selection of more cognitively capable individuals? Perhaps the more highly rated pilots were able to gain their ratings because of stronger abilities, such as greater WM capacity.

2. Regarding age and expertise, are age differences in communication task performance explainable in terms of a decrease in domain-general WM, even as aviation expertise increases?

Supplementary Analyses of Aviation Experience and Cognitive Ability Measures: Mediators of Effects of Expertise and Age

Table 4 shows the intercorrelations among age, aviation ratings, hours of flight experience, cognitive ability measures, and the overall number correct on the aviation communication task. The total accumulated hours of flight experience did not correlate with communication task accuracy, $r_s = -.01$. The reported number of flights flown per month in the past year also did not correlate with communication task accuracy, $r_s = .10$. These two findings suggest that the effect of expertise was not mediated through sheer activity or time spent aviating. Rather, the beneficial effect of expertise seen in this study may better be explained by training and "deliberate practice" (Ericsson, Krampe, & Tesch-Romer, 1993) to reach the proficiency necessary to acquire ratings or certifications beyond the private pilot license and VFR rating.

However, a selection effect may mediate or underlie the influence of expertise seen in this study. For example, pilots who attempt advanced training and pass proficiency examinations may tend to have stronger cognitive abilities. To check for selection bias, we compared the composite ability scores of the three aviation ratings groups. The scores for WM span, speed, and interference control (see Table 1) were each analyzed using a general linear model approach. Here, the main effect of interest was expertise as indexed by aviation ratings. (Also included in the model were the effect of age and the Expertise × Age interaction.) Regarding the question of participant selection bias, participants with greater aviation expertise did not have significantly better WM span scores, $F(1, 93) = 1.24$, $p > .25$, nor did they have significantly better scores for the measure of interference control ($F < 1$). There were group differences for the composite speed-of-processing score, $F(1, 93) = 5.57$, $p < .02$. Surprisingly, the VFR group was fastest, on average, and the CFII/ATP group was slowest. As shown in Table 1, this ordering was seen for both of the individual tests that made up the composite speed measure. In summary, the better performance of the more expert pilots was not explainable by superior scores on the domain-general measures of cognition.

Next, we explored the extent to which age differences in aviation communication task performance might be mediated by differences in WM span. General linear modeling revealed significant age-related differences in WM span, as well as in speed and in interference control (F values are listed in the lower portion of Table 3), with older pilots performing worse on average. These findings are remarkable considering that the participants were healthy and from a relatively restricted age range (45–69 years). The correlation coefficients ranged from −.30 to −.39, which also indicates substantial overlap among younger and older participants. None of the Age × Expertise interactions were significant ($ps > .10$). As such, there was no evidence for smaller age–cognition relations in groups with higher levels of expertise.

Statistical control procedures (Salthouse, 1996) can be used to illustrate the extent to which age-related differences in aviation communication task performance can be explained as differences in WM span. This modeling approach revealed that controlling for differences in WM span resulted in a moderate attenuation of the age effect seen in aviation communication task performance. These procedures also examined whether expertise moderated the impact of having a low WM span score (an Expertise × WM

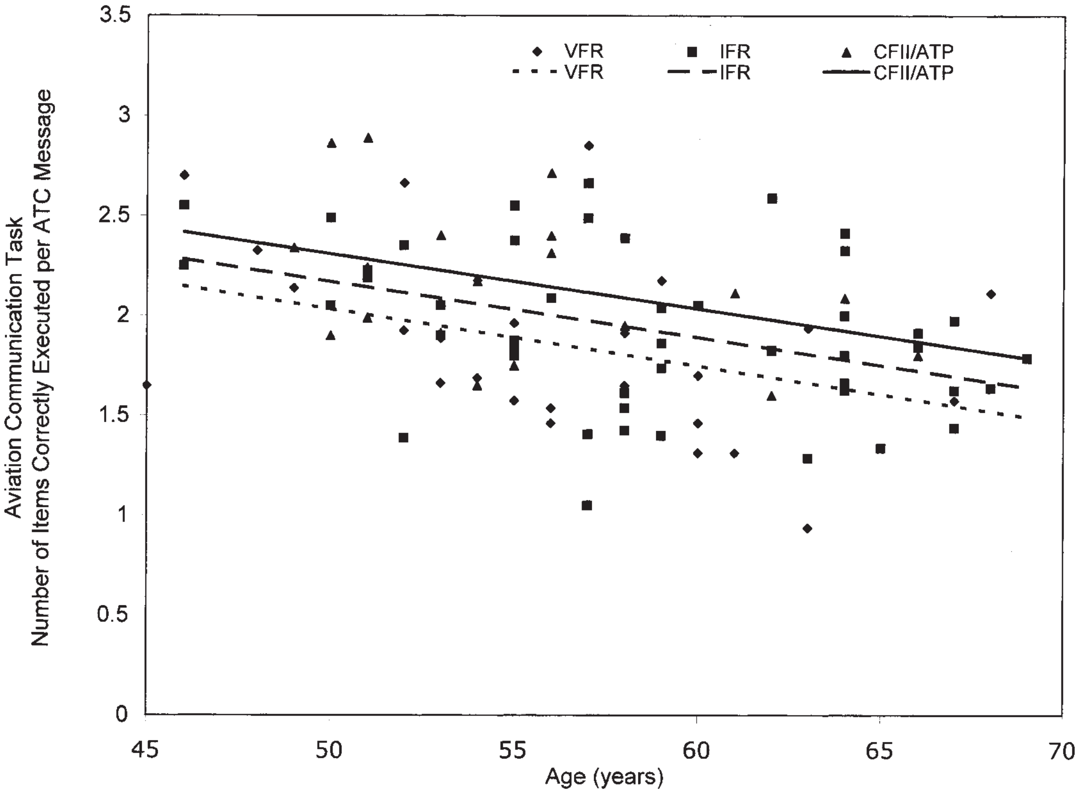

Figure 2. Aviation communication task performance: Scatter plot of overall accuracy score according to age and aviation rating. Age–performance trend lines are shown for each aviation rating group as per the parameters estimated by a general linear model: Predicted number correct = 1.975 – 0.028*(Age-57) + 0.1414*(Rating-2) + 0.00057*(Age-57)*(Rating-2), where Rating of 1, 2, or 3 represents VFR, IFR, and CFII/ATP, respectively. VFR = rated for flying under visual conditions; IFR = instrument rated, which allows a pilot to fly in clouds by using cockpit instruments to navigate; CFII/ATP = certified flight instructor of pilots in training for IFR and/or certified to fly large air-transport planes.

interaction). There was little evidence that an age-associated decrease in WM span mattered less as aviation expertise increased. Specifically, we statistically controlled for differences in WM span using hierarchical regression. In this model, expertise was entered first, then WM span, then the Expertise × WM interaction term, and, lastly, age. Statistically significant effects of expertise, WM span, and age were obtained, *F*s(1, 92) = 13.89, 138.97, and 9.66, respectively ($p < .01$), whereas the Expertise × WM Span interaction was not significant ($F < 1$). Before statistical control, age alone accounted for roughly 16% of the variance in communication task performance. After control, age accounted for 4% of the variance. This amounts to a 76% attenuation of the age effect ([15.9% – 3.8%]/15.9% = 76%). By Salthouse's schema for mediator effect sizes, an attenuation above 40% signals an "im-

Table 4

Intercorrelations (Spearman Correlation Matrix) Among Age, Aviation Ratings, Flight Time, Cognitive Ability Measures, and Aviation Communication Task Performance (Overall Score)

Variable	1	2	3	4	5	6	7	8
1. Age	—	−0.30	−0.39	−0.33	−0.04	0.19	−0.14	−0.41
2. Working memory span composite score		—	0.31	0.43	0.12	−0.14	0.01	0.76
3. Speed composite score			—	0.20	−0.20	−0.30	−0.13	0.33
4. Interference control composite score				—	−0.01	−0.17	−0.03	0.43
5. Aviation rating					—	0.57	0.21	0.23
6. Total no. of flight hours logged						—	0.21	−0.01
7. Average no. of flights/month in past year							—	0.10
8. Aviation communication task performance (overall score)								—

Note. Spearman correlation coefficients of an absolute magnitude ≥ .20 were significant ($p < .05$).

portant" mediating construct (Salthouse, 1992a). The attenuation of the age effect here reflects conditions in which (a) WM span scores strongly predicted the accuracy of executing ATC messages, $r_s = .75$; and (b) WM span scores correlated with age, $r_s = -0.30$. Because the Expertise × WM Span interaction was not significant, there is little evidence that an age-associated decrease in WM span mattered less as aviation expertise increased. Thus, it appears that in this study, an age-associated decline in WM span could account for age differences in aviation communication task accuracy regardless of level of expertise.[1]

Finally, we report results of statistical control procedures to illustrate the extent to which age-related differences in WM span may, in turn, be explainable as differences in speed and interference control. Before statistical control of speed and interference, age accounted for 8.1% of variance in WM span scores, $F(1, 95) = 8.37$, $p < .01$. After statistical control of speed alone, age accounted for 3.0% of the variance. After statistical control of differences in interference alone, age accounted for 2.7% of the variance. After statistical control of both speed and interference, age accounted for 0.7% of the variance. Thus, variability in speed and interference control together could explain about 90% of the age-related differences in WM span performance ([8.1% – 0.7%]/8.1% = 91%). Specifically, speed, interference control, and age were entered as terms in that order in a hierarchical regression model predicting WM span scores. Speed was a significant source of variance, $F(1, 93) = 12.29$, $p < .01$, incremental $R^2 = .10$; interference control was a significant source of variance, $F(1, 93) = 17.07$, $p < .01$, incremental $R^2 = .14$; but the .007 increment in R^2 associated with age was not statistically significant ($F < 1$). The large attenuation of the age effect here reflects conditions in which (a) speed and interference control scores each correlated moderately with WM span scores and with age, and (b) speed and interference control scores correlated weakly with each other (.20), which rendered their common variance with age fairly small (approximately 3% shared variance).

Discussion

In this study of pilots' accuracy of executing ATC instructions from memory, the expected effects of age and expertise were obtained: Older pilots were less accurate than younger pilots on average, and more highly trained pilots were more accurate than less trained pilots. No significant interaction between age and expertise was observed, however. The size of the age effect on aviation communication performance was about as large as that observed on the WM, speed, and interference control measures. Thus, we found no evidence that performance of the domain-relevant task was better maintained across the age range in contrast to performance of the domain-general cognitive tasks. At the same time, it is important to emphasize the considerable overlap of scores between younger and older individuals seen in all measures of performance, as illustrated by the moderate-sized correlation coefficients of Table 4.

In contrast to the pervasive negative age-related differences in performance, a positive effect of expertise was seen in the domain-relevant task. The most expert pilots, those trained in instrument procedures and rated for air transport or certified for advanced flight instruction, performed at an accuracy level that was about 20% higher than that of pilots whose formal training ended after initial student training to obtain a basic pilot license. The benefit of advanced training was not explained by a selection effect nor was it explained purely in terms of an accumulation of hours spent in flying activities. Specifically, we found no evidence that pilots who had achieved higher ratings or certifications scored higher on cognitive ability measures on average. Second, neither total flight time nor amount of recent flying activity correlated with communication task performance. Taken together, these findings lend further support to the thesis that deliberate, formal training is more central to acquisition of expertise than is simply the amount of time spent in performance (Ericsson et al., 1993).

Potential limitations of this study include the somewhat restricted ranges of pilot expertise and age. In contrast to this study, Morrow et al. (2001) compared differences in aviation communication task performance between nonpilots and pilots sampled from a very wide age range (26–84 years). It is interesting to note that the relation of age to two measures of communication task performance was no greater there than that seen in this study. On the other hand, Morrow et al.'s composite measure of expertise accounted for 27% of the variance in performance, in contrast to the modest 5% of variance explained in the present study. The modest effect of expertise demonstrated here would make it more difficult to detect an Age × Expertise interaction. However, Morrow et al. (2001) also failed to obtain Age × Expertise interactions (Fs < 1), despite wide ranges of age and aviation expertise. Another potential limitation of the study is that we did not try to measure the level of performance accuracy expected for a pilot flying solo under typical flight conditions. In real flight, proper execution of ATC instructions is typically supported by several aids, including use of a knee pad for note taking, a cockpit instrument marker or "bug" pointing to the desired heading, and ability to have the ATC repeat the instructions. We did not allow use of these aids because of our interest in relating cognitive function to aviation conditions with high task demand.

Strengths of this study are the lack of a strong confound of age with the expertise and flight experience measures, the experimental manipulation of speech rate and message length with the aim of varying demands on WM, and the use of a flight simulator to enhance task relevance. Although faster speech rates and longer

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[1] The same statistical control procedures used to examine working memory span as a cognitive "mediator" of age differences in aviation communication performance can also be applied to the speed and interference control measures. The hierarchical regression model would include a term for expertise (as indexed by aviation ratings), a term for speed (or interference), a term for the interaction of expertise with speed (or interference control), and, lastly, a term for age. We performed these analyses for comparative purposes. In the "Expertise, Speed, Expertise × Speed" model, the Expertise × Speed interaction was not significant ($F < 1$), whereas the other terms, including age, were statistically significant at $p < .01$. The increment in R^2 associated with age after control of other predictors was .05, that is, a 66% attenuation of the age effect. In the "Expertise, Interference, Expertise × Interference" model, the Expertise × Interference interaction was not significant ($F < 1$), whereas the other terms were ($p < .01$). The increment in R^2 associated with age after control of other predictors in this model was .079, that is, a 50% attenuation of the age effect. Thus, by Salthouse's (1992a) schema for mediator effect sizes, any one of these variables—WM span, speed, or interference control—signals what could be an "important" mediator of age differences in cognition.

message lengths impaired accuracy, age-related differences in accuracy did not increase with greater message difficulty, and neither did expertise-associated differences vary significantly. Wingfield and colleagues manipulated speech rate and demonstrated that age-related differences in immediate recall performance increased (Riggs et al., 1993; Stine et al., 1986; Tun, 1998; Tun et al., 1992; Wingfield et al., 1985), especially when the stimuli are random words (Wingfield et al., 1985). Yet Age × Speech Rate interactions have been obtained using natural sentences (Riggs et al., 1993; Stine et al., 1986; Tun, 1998; Tun et al., 1992; Wingfield et al., 1985), so it is somewhat surprising that we did not find a significant interaction. Possible reasons for negative results include variation of the speech rate over a narrower range in this study, the narrower age range, and perhaps most important, the selection of expert participants and use of aviation terms and phraseology. ATC language is a restricted vocabulary with standard, ordered phrases that increase redundancy and predictability of information. These experimental design and language parameters, alone or in combination, may limit the power to detect Age × Speech Rate and Expertise × Speech Rate interactions.

It is noteworthy that a pilot's execution accuracy was strongly predicted by the WM span composite score ($r = .76$). Supplemental analyses addressing mediators of age-related differences in aviation task accuracy revealed that the WM span measure could largely account for the age-related differences seen in aviation communication task performance. Roughly 75% of the age–performance relation could be accounted for by differences in WM span. Furthermore, roughly 90% of the age–WM span relation could be explained on the basis of slower speed and decreased interference control. Two prior studies have stressed the important roles of both speed of processing and control of interference in explicating age differences in reading performance and in WM efficiency (Kwong See & Ryan, 1995; Van der Linden et al., 1999). This study extends results to language performance based on auditory presentation and strengthens arguments that models of age differences in WM may be most complete when both speed and control of interference are included. In conclusion, processing speed and interference control are emerging as two fluid processes integral to the efficiency of WM that may decline with age and may impact the performance of tasks that depend on WM. In the following section, we relate this position to prior findings in the cognitive aging literature. Then we come back to expert knowledge and revisit evidence as to when expertise mitigates the impact of age-related declines in fluid, domain-general abilities.

Slower Speed and WM

Cognitive slowing could be expected to impair WM and short-term recall in multiple ways—during encoding, during rehearsal, and during retrieval. If the listener cannot keep up with the pace of presentation, the information may be incompletely encoded. Once encoded, an item may be more likely to be lost from WM if rehearsal takes place more slowly. Three prior studies implicated slower rehearsal as a source of age differences in immediate recall (Bryan & Luszcz, 1996; Kynette, Kemper, Norman, & Cheung, 1990; Multhaup, Balota, & Cowan, 1996). Bryan and Luszcz (1996) directly measured articulation speed and found that statistical control of articulation speed attenuated age-related variance in free recall by 19%. Kynette et al. (1990) and Multhaup et al. (1996) found that older adults had slower word repetition rates and lower span scores and that slower repetition rates predicted a smaller span. Taken together, these studies suggest that a slower rate of rehearsal leads to less information being recalled. However, rehearsal rate may not be the sole mediator, as Bryan and Luszcz pointed out, because age differences in immediate recall were only partially explained by slower articulatory rate. Digit Symbol scores, which Bryan and Luszcz took to be a measure of general information processing speed, explained a much larger portion of the age-related variance (91% reduction with Digit Symbol vs. 19% reduction with articulatory speed). This suggests that slower rehearsal is but one consequence of slower processing speed.

Interference

Evidence on three fronts implicates interference susceptibility as key to appreciating age differences seen in the performance on WM tasks. First, Hasher, Lustig, May, and colleagues suggest that typical WM span assessments also reflect susceptibility to interference (Lustig & Hasher, 2002; Lustig, May, & Hasher, 2001). Their work varying the order of list lengths (either progressively longer lists or progressively shorter lists) has led them to argue that older adults' lower span scores reflect an increased sensitivity to proactive interference (Lustig et al., 2001). Studies of retroactive interference also suggest an age-associated increase in susceptibility to interference in verbal WM (Hedden & Park, 2001). Third, when interference is increased by making the processing and to-be-remembered items similar in a loaded span task, older adults are more impaired by this manipulation than are younger adults (Li, 1999). Each of these studies supports the interference account of age differences in WM.

The primary measure of interference in this study was the Shifting Attention Discovery Test. Better performance on this measure presumably reflects ability to suppress interference between competing stimulus dimensions and from previous task rules that are no longer relevant. As with the Wisconsin Card Sorting Test, this measure likely invokes several aspects of control over processing. Age differences in inhibitory control, task switching, and interference suppression in WM tasks have been related to age differences in measures of frontal lobe integrity, as measured by functional (Jonides et al., 2000; Smith et al., 2001) and structural MRI (Raz, Gunning-Dixon, Head, Dupuis, & Acker, 1998). Various versions of a frontal lobe hypothesis of cognitive aging (Arbuckle & Gold, 1993; Dempster, 1992; West, 1996) imply that an inhibitory control, interference, and source-monitoring ability can be assessed. More definitive psychometric and factor analytic work is sorely needed in this area, as many measures of inhibitory control, task switching behavior, and the like (including the Shifting Attention test) lack established reliability and construct validity. That these measures should not largely overlap with general speed of processing measures is a refrain vocalized by numerous previous investigators (Bryan & Luszcz, 2000; Burke, 1997; Luszcz & Bryan, 1999; McDowd, 1997; Park et al., 1996; Rabbitt, Lowe, & Shilling, 2001; Salthouse, 1999).

When Expertise Reduces Age Differences

Even among the pilots deemed experts, domain-general measures of WM strongly predicted the accuracy of executing aviation communications. Meinz (2000) noted that the largest group of studies not finding evidence for an age-moderating effect of expertise were studies involving recent episodic memory. The skilled memory tests included recall or reproduction of meaningfully arranged chess pieces (Charness, 1981a, 1981b), memory for bridge hands (Charness, 1979), musical memory by written recall and by piano keyboard execution (Meinz, 2000; Meinz & Salthouse, 1998), read-back of aviation communications and recall of aircraft routes (Morrow et al., 1994, 2001), and immediate memory of simulated baseball game broadcasts (Hambrick & Engle, 2002). Researchers have suggested that expertise should moderate age effects when the task is domain relevant (see Morrow et al., 2001, for a review). Because the aforementioned studies did meet the criterion of task-domain relevance, but did not obtain significant Age × Expertise interactions, task-domain relevance may be a necessary condition for expertise to moderate the effect of age, yet it does not appear to be a sufficient one.

Current theoretical models of expertise and aging propose that expertise may reduce the impact of age-related cognitive decline by means of task automation, compensation, or both. This particular type of expertise can be used to explain the lack of age differences seen among skilled typists in the speed-typing natural language digraphs (e.g., "he"; Bosman, 1993). Theoretically, automated motor executions should free up limited-capacity controlled or fluid processes. The freed controlled processes might then be allocable to other aspects of task performance, such as preparing for movement. Older skilled typists, for example, appear to plan finger movements earlier than less experienced typists, as measured by how far ahead they look at text during transcription typing (Bosman, 1993; Salthouse, 1984). In summary, the best evidence for an age-moderating effect of expertise comes from studies of perceptual and motor skills, in which expert performers have the advantage of more automated responding and potentially more spare capacity than novice performers.

In contrast to perceptual and motor skills, episodic memory for domain-relevant stimuli may involve starkly different demands on limited WM capacity. It has been proposed that individuals with more knowledge of a particular domain can remember more by "chunking" features of a domain-specific stimulus during encoding (Chase & Ericsson, 1982). Ericsson and Kintsch (1995) proposed that the products of such encoding are at least partly stored in long-term memory because the encoded product is based on previously acquired knowledge. So, they argued, the traditional model of WM as a temporary storage must be extended to include information in long-term memory, which, they proposed, is accessible by means of retrieval cues maintained in short-term memory. Their model was designed to account for how experts use knowledge to circumvent limitations of short-term WM in order to recall more information than those with less knowledge of the participant. However, this model is relatively new and so has not yet incorporated individual or age-related differences in short-term WM. In a recent study of baseball knowledge, age, and individual differences in WM, the beneficial effect of baseball knowledge was greater in those participants who scored higher on measures of domain-general WM capacity (Hambrick & Engle, 2002). Thus, the benefit of knowledge could decrease as WM capacity decreases. Morrow et al. (2001, 2003) agreed that memory demands can preclude expertise-based reduction of age differences in skilled performance. Similarly, Meinz and Salthouse (1998) offered that WM limitations may have affected older musicians' performance of the domain-relevant music task used in their study.

Conclusions

Age-related differences in the span of WM could account for age differences in performance of domain-relevant tasks, even among the more expert participants. In turn, age differences in WM could be explained by age-related differences in processing speed and interference control. This study adds to the growing body of literature that argues for the importance of both speed and interference control as separable factors that may contribute to age-related differences in cognitive performance (Braver et al., 2001; Kramer, Hahn, & Gopher, 1999; Kray & Lindenberger, 2000; Kwong See & Ryan, 1995; Meiran, Gotler, & Perlman, 2001; Persad, Abeles, Zacks, & Denburg, 2002; Spieler, Balota, & Faust, 1996; Van der Linden et al., 1999; Verhaeghen & De Meersman, 1998; Wecker, Kramer, Wisniewski, Delis, & Kaplan, 2000; West & Baylis, 1998). Especially important is the question of the life span development of processing speed and control of interference. It is conceivable that these two abilities could mature, peak, and decline at different rates in normal development. Clearly, longitudinal studies are needed to address this question.

Acquisition of expert knowledge and training can boost domain-relevant performance to a higher level for older and younger individuals alike. With regard to the question of when domain-specific knowledge reduces age differences in performance, research findings have been inconsistent. Morrow and associates aptly emphasized the importance of making the task under study "domain-relevant." Meinz (2000) underscored the importance of verifying that such tasks have strong age relations among inexperienced participants. We agree on both points and also stress the importance of assessing the degree to which WM and related fluid abilities contribute to performance because age-related reductions in domain-general cognitive abilities may impact performance of a domain-relevant task.

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