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Environmental Support for Older and Younger Pilots' Comprehension of Air Traffic Control Information

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We investigated whether expertise mitigates age differences on pilot communication tasks when experts rely on environmental support. Pilots and nonpilots listened to air traffic control messages describing a route through an airspace, during which they referred to a chart of the airspace. The routes were high (waypoint routes anchored to navigational reference points on the chart) or low (vector routes that were not) in contextual support. Participants read back messages and answered questions about aircraft position (which required integration of message and chart information) or altitude (which did not). Pilots more accurately answered questions. The expertise advantage for position, but not altitude, questions was greater for waypoint routes, showing differential use of environmental support by experts. Age did not moderate these effects.

THE aging population in the United States is confronted by challenges related to adapting to technological changes at home and in the workplace (Morrow & Leirer, 1997; Stern & Carstensen, 2000). Age-related performance issues are particularly relevant to aviation because, like the general population, the population of pilots (Morrow & Leirer, 1997) and air traffic controllers (Becker & Milne, 1998) is aging, prompting a need to identify potential age-related costs and benefits related to complex task performance. Moreover, the principle of universal design (Vanderheiden, 1997) suggests that improving displays, procedures, and other aspects of the aviation environment for older pilots will yield general benefits for the workforce.

We focus on two interrelated factors that may help determine the conditions under which older pilots remain proficient: expertise (knowledge and experience) related to piloting tasks and environmental support provided by these tasks. First, experts excel on domain-relevant tasks for a variety of reasons. Experts possess highly organized knowledge structures (Glaser & Chi, 1988) that enable rapid retrieval from long-term memory of information needed to accomplish the task, reducing working memory constraints on performance (Ericsson & Kintsch, 1995). Such knowledge-based mechanisms may offset age-related declines in working memory that would otherwise constrain performance of complex tasks. However, evidence that expertise mitigates age declines is equivocal (see Hambrick & Engle, 2002; Meinz, 2000). Conflicting evidence for mitigation may reflect variation across studies in task characteristics, such as complexity or domain relevance (Morrow & Leirer, 1997). Domain-relevant tasks are organized around domain goals and constraints (Vicente & Wang, 1998).

A second factor that may influence older pilots' proficiency on complex tasks is the environmental support provided by domain-relevant tasks, which may support experts' use of knowledge to accomplish task goals (Kirlik, 1995). Environmental support may especially benefit older experts and mitigate age declines in cognitive abilities because older experts are adept at using external aspects of the task environment to reduce demands on cognitive resources (e.g., working memory). Although the concept of environmental support is multifaceted (Morrow, 2003), we focused on the extent to which the task externalizes mental processes that would otherwise be required by the task, which addresses age-related problems associated with self-initiating mental processes (Craik & Jennings, 1992). For example, relying on external parts of the cockpit (e.g., displays and charts) can reduce the pilot's need for memory retrieval and other cognitive processes (Hutchins, 1991).

We examined whether a navigational chart (a typical part of pilots' cockpit environment) supports pilots' comprehension of air traffic control (ATC) messages. To understand potential benefits of the chart, we briefly describe comprehension processes in ATC communication. Pilots routinely receive radio messages to change their aircraft's course (among other instructions). Understanding these messages involves word recognition and parsing of syntactic structure, which enables identification of the semantic content of the message. Perhaps what is most important is that the message information must be interpreted in terms of and integrated with information provided by flight instruments and other components of the flight context (both inside and outside the cockpit) in order to create a situation model (or mental model) of the current and projected flight conditions, so that the pilot understands not only what to do but how it will influence the flight situation (see Kintsch, 1998, for a general model of comprehension processes). This representation supports situation awareness, the ability to monitor the current and projected aircraft route and flight conditions (Adams, Tenney, & Pew, 1995). Pilots also read back (repeat) ATC messages, allowing the controller to verify their comprehension of the messages. Understanding ATC messages and updating the situation model should impose heavy demands on working memory (Morrow & Rodvold, 1998) and spatial

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We measured message comprehension by asking questions about aircraft position or altitude presented after participants listened to and read back instructions from the message. Only the position questions required integration of message and chart information (see Figure 1). Pilots' comprehension of the waypoint routes should be supported by the chart, which provides perceptual information about the route. This domain-relevant environmental support should help them update a precise situation model of the aircraft's current position and projected route. Nonpilots' comprehension should benefit less from the chart in the waypoint route condition because they have little if any experience using navigational aids as environmental support for integrating message and chart information. Differential expertise benefits are more likely for position than for altitude questions, because only the position questions require integration. Older pilots' comprehension (for position but not altitude questions) should especially benefit from the chart in the waypoint condition, which helps reduce the self-initiated processes required to update the situation model.

Comprehension of the vector routes is less supported by the chart, which does not directly indicate the route. In this case, pilots receive less environmental support for updating their model (e.g., they must infer the exact aircraft position from chart and message information). This in turn may increase the amount of cognitive resources necessary for updating, which may disadvantage older pilots. Earlier studies found that expertise does not reduce age differences in comprehension of vector routes (Morrow et al., 2003). Thus, the navigation chart should serve as a domain-relevant environmental support for pilots' comprehension of ATC information, primarily in the waypoint condition. On the basis of previous studies, we also expected pilots to more accurately read back ATC messages. However, support from the chart in the waypoint condition is unlikely to improve readback accuracy because this task does not require integration of message and chart information.

We also explored sources of age and expertise differences in performance on the question and readback tasks. As in our earlier studies (Morrow et al., 2001; Morrow, Menard, et al., 2003), we used regression analyses to investigate the extent to which age and expertise effects were explained by individual differences in working memory, speed of mental processing, and spatial ability (see the Methods section for a description of these measures). The analyses also provided an opportunity for us to investigate whether age was moderated by expertise, when age and expertise are measured as continuous variables (see the Methods section for a description of expertise measures). Moderation would be indicated by significant Age 3 Expertise interaction terms after we controlled for the main effects of age and expertise. We also examined whether expertise mediated age declines because the older pilots had higher levels of experience (more flying hours) than the younger pilots did, which may buffer against age-related declines in cognitive abilities. Mediation would be indicated by finding that age accounts for more variance in performance when expertise is controlled in the regression analysis, suggesting that the older pilots would have been even more impaired if they could not rely on relatively higher levels of experience (Meinz, 2000; Morrow et al., 2001).

METHODS

Participants

Participants were 92 pilots medically certified to fly and with high levels of experience (minimum of 700 flying hours) in airline or corporate operations (age range, in years: young or Y¼ 22–40; middle-aged or M¼ 50–59; older or O¼ 60–76), as well as 96 nonpilots (age range, in years: Y¼ 25–39; M¼ 50–59; O¼ 60–73). Pilots were less educated than nonpilots but rated themselves as healthier (see Table 1). The mean age of the young nonpilots was lower than that of the young pilots, F(1, 62) ¼ 9.6, p , .01, but pilots and nonpilots in the middle-aged and older groups did not differ in mean age, F(1, 62) , 1.0, producing a significant Age 3 Expertise interaction, F(2, 182) ¼ 4.8, p , .01. (The pattern of results from analyses reported in this article was unchanged when we eliminated the youngest nonpilots in order to equate the age range for the nonpilot and pilot groups.)

We measured cognitive abilities relevant to the aviation tasks to ensure that experts and novices were comparable in general abilities. We measured vocabulary by using the Advanced Vocabulary Test from the Kit of Factor-Referenced Cognitive tests, which is an 8-min test containing 36 multiple-choice items (Ekstrom, French, Harmon, & Dermen, 1976). We measured verbal working memory capacity by using a loaded listening and reading sentence span test that measures the ability to simultaneously store and manipulate verbal information in memory. Participants responded true or false to progressively larger sets of spoken or printed sentences (between two and eight sentences) and then recalled the last word of each sentence in the set. The span score is the size of the largest set for which participants could recall all the sentence-final words (for details on materials and scoring, see Stine & Hindman, 1994). We measured processing speed by using the Letter Comparison and Pattern Comparison tasks (Salthouse & Babcock, 1991). In these paper-and-pencil tests, participants decided as rapidly as possible whether pairs of letter sets or line patterns were the same or different. We measured spatial ability with the Wechsler Adult Intelligence Scale–Revised (WAIS-R) Block Design test (Wechsler, 1981). In this task, participants were required, in a given period of time, to reconstruct a pattern shown on a card from a set of blocks. Whereas the vocabulary test is thought to be a measure of crystallized or knowledge-based ability, the sentence span, comparison, and Block Design tests are thought to measure fluid abilities, which require efficient processing of novel information (Salthouse, 1991).

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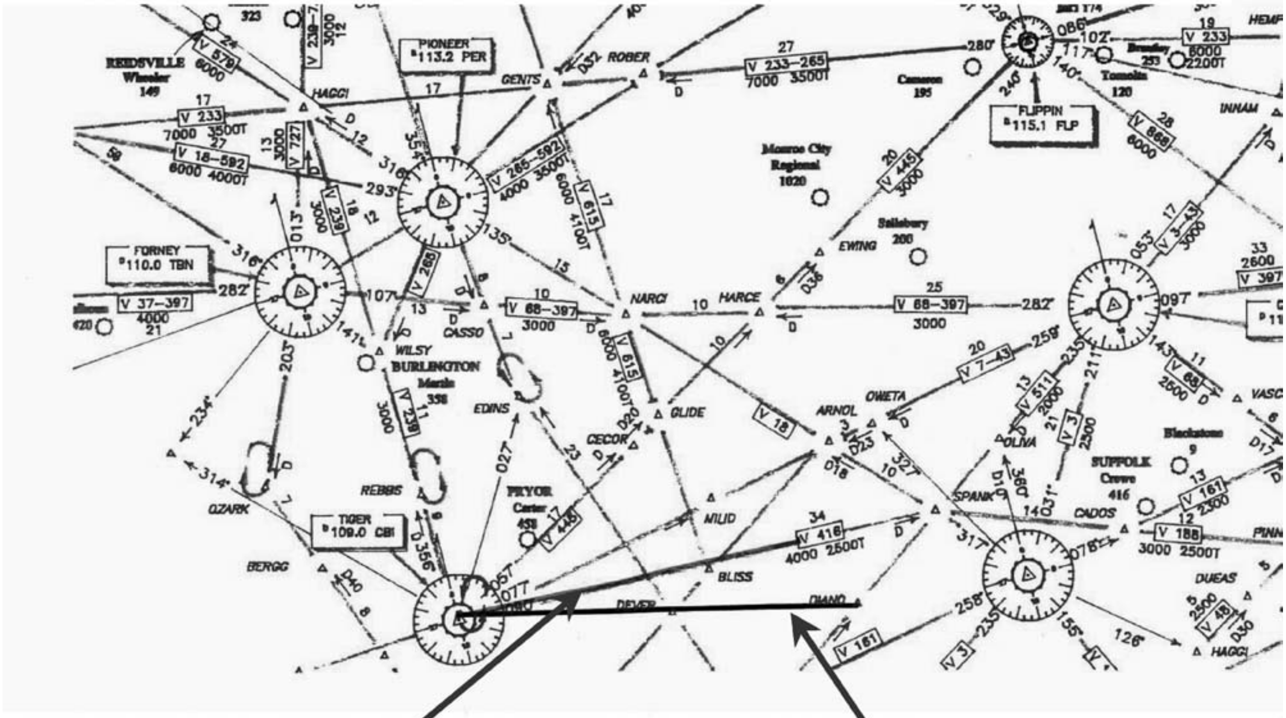
Flight Plan:

…TIGER VOR..V416..SPANK Intersection …V188..CADOS Intersection..V161..LINDEN..V66..HADIK Intersection.. Radar Vectors…POGUE INT'L AIRPORT



Waypoint Route (on airway)

Message 1: You are overhead TIGER VOR heading northeast, at FL220, flying at 310 knots.

Cross 9 miles west of SPANK Intersection
At FL180
And 300 knots

Position Probe Question:
After 5 minutes, the aircraft's position would be:
a) 5 miles past the crossing restriction.
b) Overhead the crossing restriction.
c) 3 miles short of the crossing restriction.

Altitude Probe Question:
Once level at assigned altitude, an aircraft flying across your flight path would pose a conflict if:
a) Climbing from FL 180.
b) Level at 17,000 feet.
c) Descending from 16,000 feet

Vector Route (off airway)

Message 1: You are overhead TIGER VOR heading northeast, at FL220, flying at 310 knots.

For weather, turn right heading 105
Descend and maintain FL180
Reduce speed to 300 knots

Position Probe Question:
If the aircraft continued on its present heading, would the aircraft pass closer to:
a) Overhead BLISS Intersection.
b) Overhead DIANO Intersection.
c) A point 3 miles south of DIANO

Altitude Probe Question:
Same as waypoint route

Figure 1. Example of waypoint and vector routes, and position and altitude questions.

There was a typical age-related increase for vocabulary and age declines for the verbal working memory, processing speed, and spatial ability measures. Pilots and nonpilots did not differ in vocabulary, span, or block design scores, but nonpilots exhibited higher scores on the comparison tasks. What was most important was that the Age × Expertise interactions were not significant for the fluid ability measures, showing that the pilots experienced typical age-related declines in these abilities (see Table 1).

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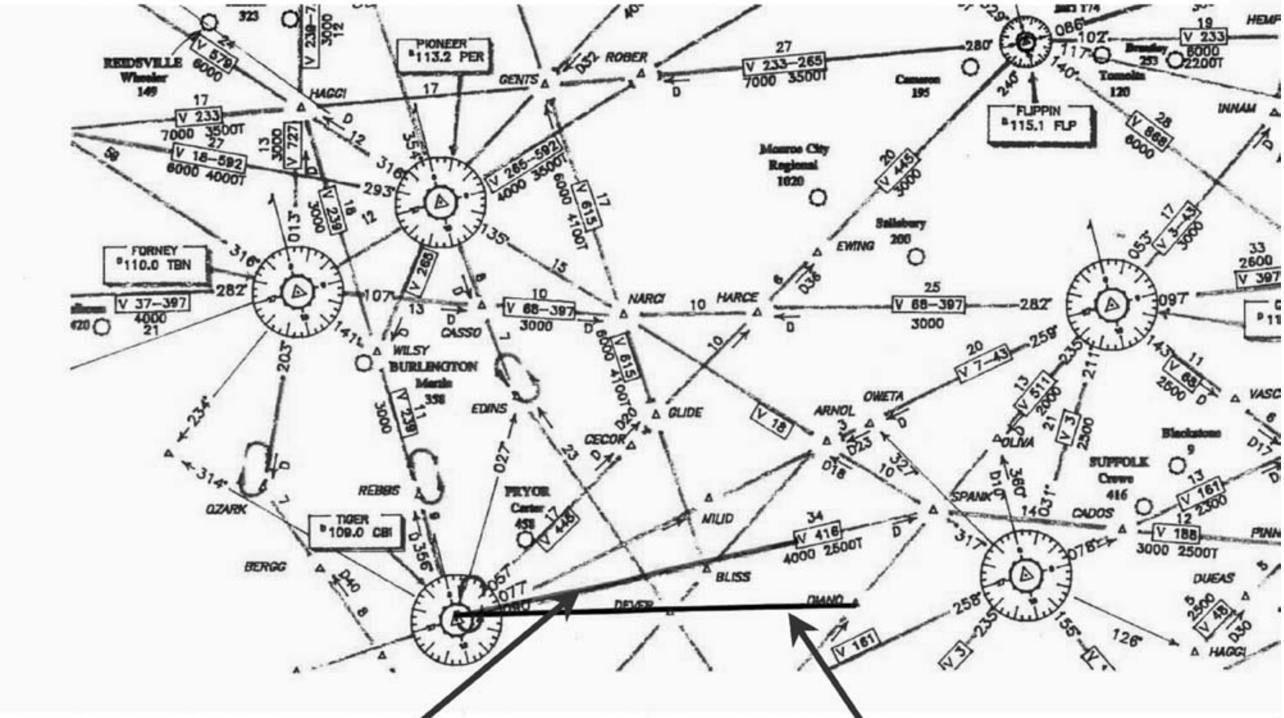

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Table 1. Demographic and Cognitive Ability Scores

	Pilots			Nonpilots				
Variable	Y	M	O	Y	M	O	Expertise	Age
Age								
M	32.9	54.6	65.5	29.3	55.0	65.8	3.1	
SE	0.72	0.72	0.72	0.72	0.72	0.72		
Education								
M	16.2	16.1	15.0	17.1	17.4	16.9	14.9**	2.4
SE	0.41	0.41	0.43	0.41	0.41	0.41		
Health[a]								
M	6.1	6.0	6.4	5.9	5.7	5.6	8.6**	, 1.0
SE	0.19	0.19	0.20	0.19	0.19	0.19		
Vocabulary[b]								
M	17.9	24.2	24.2	20.5	25.4	25.0	3.0	20.4**
SE	0.99	0.99	1.06	0.99	1.06	0.99		
Span[c]								
M	4.6	4.2	3.6	4.4	4.0	3.5	2.5	25.0**
SE	0.14	0.14	0.15	0.14	0.14	0.14		
Comp.[d]								
M	31.0	27.6	25.0	34.1	28.3	24.9	4.0*	53.7**
SE	0.73	0.73	0.78	0.73	0.74	0.73		
Block design[e]								
M	43.7	38.4	36.3	43.8	39.0	31.9	1.5	31.6**
SE	1.20	1.20	1.28	1.20	1.22	1.20		
Knowledge[f]								
M	15.3	14.0	13.3	8.0	8.2	7.3	373.9**	5.1*
SE	0.40	0.40	0.43	0.40	0.45	0.40		

Notes: Y ¼ young; M ¼ middle-aged; O ¼ older. For Y, M, and O pilots, *n* ¼ 32, 32, and 28, respectively. For Y, M, and O nonpilots, *n* ¼ 32, 32, and 32, respectively. For Expertise, *F*(1, 178), which is an *F* test comparing pilot and nonpilot groups. For Age, *F*(2, 178), which is an *F* test comparing Y, M, and O groups.

[a] Self-reported health: 7 ¼ excellent health, 1 ¼ very poor health.

[b] Advanced Vocabulary Test from the Kit of Factor-Referenced Cognitive tests (Ekstrom, French, Harmon, & Dermen, 1976).

[c] Sentence span task (Stine & Hindman, 1994).

[d] Letter and Pattern Comparison tasks (Salthouse & Babcock, 1991).

[e] WAIS-R Block Design test (Weschler, 1981).

[f] Domain-knowledge questionnaire about aviation navigation and air traffic control communication concepts (adapted from an FAA instrument rating exam; Morrow et al., 2001).

**p* , .05; ***p* , .01.

Participants also completed several measures related to piloting expertise. All pilots had commercial licenses and were instrument rated (i.e., certified to fly under instrument as well as visual flight conditions). Age was associated with more total flying hours (Y¼6,149 mean hr, M ¼ 17,067, O ¼ 19,193), *F*(2, 89)¼35.8, g$_2$ ¼.45, Y , M¼O, but fewer recent hours (Y¼627 mean hr, M ¼ 617, O ¼ 194), *F*(2, 89) ¼ 26.0, g$_2$ ¼ .37, Y ¼ M - O. We assessed domain knowledge by using a questionnaire about aviation navigation and ATC communication concepts with 20 multiple-choice items (adapted from an FAA instrument rating exam; test–retest reliability, *r* ¼ .79; Morrow et al., 2001). Of course, pilots outscored nonpilots on this measure (see Table 1). Age had a small but reliable influence (g^2 ¼ .05) and did not interact with expertise. Thus, although older pilots experienced declines in general cognitive abilities typical of their cohort, on average they had more flying experience than their younger counterparts, and they experienced only small declines on a measure of aviation-related declarative knowledge.

Materials

Navigation chart. —As in the research by Morrow and colleagues (2001), we used a low-altitude en route chart for the northeastern United States airspace with names of navigation reference points changed to make the specific content unfamiliar to pilots. The chart indicated the location of electronic navigational reference points that define standard routes used by commercial aircraft to fly into (approach) or out of (departure) the terminal airspace of surrounding airports. These included radio beacons (VOR, or very-high-frequency omnirange), radials (which radiate off VORs like spokes from a wheel), and Victor airways (part of the low-altitude VOR system that defines standard aircraft routes).

ATC messages. —Participants listened to ATC messages that described four routes through this airspace. There were two waypoint and two vector routes, with presentation order counterbalanced across participants. Each route was accompanied by a flight plan (typed on a 3 in. **3** 5 in., or 7.5 cm **3** 12.5 cm, card) indicating a series of VORs, intersections, and connecting Victor airways that identified the intended route (see Figure 1). The route was described by six ATC messages, each corresponding to a leg of the route. Each message began with an aircraft position report (identifying the location and direction of the aircraft when the ATC message is received; this information is not typically part of ATC messages but was necessary for our study) followed by three instructions to change the course of the aircraft, presented in the order specified by the *ATC Handbook* (FAA Order 7110.65): heading, altitude, and speed. As Figure 1 shows, waypoint routes were defined by navigational aids on the chart (on an airway). Instructions were presented in the form of crossing restrictions for position, altitude, and speed instructions (the aircraft was instructed to cross a position in the airspace that was defined relative to a navigational aid such as a VOR or intersection, at a particular altitude and speed). Vector routes, in contrast, were defined by headings that were not anchored to the aids (i.e., off airways). In other words, the vector routes deviated from the original flight plans (to avoid traffic congestion or bad weather). Airline pilots are likely to receive both kinds of route instructions when flying into or out of terminal airspace. All messages were recorded by a retired terminal controller using a speech rate typical of actual ATC operations.

We measured message comprehension by using questions about the aircraft's route. Half of the questions probed the position of the aircraft on the route by asking which of three positions the aircraft would pass closest to if it continued on the assigned course (*position* questions). Some position questions involved computing a projected position from the current aircraft position, which required time/speed calculations that should also be facilitated by environmental support (the chart) in the waypoint condition. The other half of the questions probed the aircraft's assigned altitude by asking which of three other aircraft on the same flight path but at different altitudes would pose a conflict. In other words, if both the participant's aircraft and each of these three aircraft continued on their present course, the participant's aircraft would potentially collide with

Table 1. Demographic and Cognitive Ability Scores

	Pilots			Nonpilots				
Variable	Y	M	O	Y	M	O	Expertise	Age
Age								
M	32.9	54.6	65.5	29.3	55.0	65.8	3.1	
SE	0.72	0.72	0.72	0.72	0.72	0.72		
Education								
M	16.2	16.1	15.0	17.1	17.4	16.9	14.9**	2.4
SE	0.41	0.41	0.43	0.41	0.41	0.41		
Health[a]								
M	6.1	6.0	6.4	5.9	5.7	5.6	8.6**	<1.0
SE	0.19	0.19	0.20	0.19	0.19	0.19		
Vocabulary[b]								
M	17.9	24.2	24.2	20.5	25.4	25.0	3.0	20.4**
SE	0.99	0.99	1.06	0.99	1.06	0.99		
Span[c]								
M	4.6	4.2	3.6	4.4	4.0	3.5	2.5	25.0**
SE	0.14	0.14	0.15	0.14	0.14	0.14		
Comp.[d]								
M	31.0	27.6	25.0	34.1	28.3	24.9	4.0*	53.7**
SE	0.73	0.73	0.78	0.73	0.74	0.73		
Block design[e]								
M	43.7	38.4	36.3	43.8	39.0	31.9	1.5	31.6**
SE	1.20	1.20	1.28	1.20	1.22	1.20		
Knowledge[f]								
M	15.3	14.0	13.3	8.0	8.2	7.3	373.9**	5.1*
SE	0.40	0.40	0.43	0.40	0.45	0.40		

Notes: Y = young; M = middle-aged; O = older. For Y, M, and O pilots, $n = 32$, 32, and 28, respectively. For Y, M, and O nonpilots, $n = 32$, 32, and 32, respectively. For Expertise, $F(1, 178)$, which is an F test comparing pilot and nonpilot groups. For Age, $F(2, 178)$, which is an F test comparing Y, M, and O groups.

[a] Self-reported health: 7 = excellent health, 1 = very poor health.

[b] Advanced Vocabulary Test from the Kit of Factor-Referenced Cognitive tests (Ekstrom, French, Harmon, & Dermen, 1976).

[c] Sentence span task (Stine & Hindman, 1994).

[d] Letter and Pattern Comparison tasks (Salthouse & Babcock, 1991).

[e] WAIS-R Block Design test (Weschler, 1981).

[f] Domain-knowledge questionnaire about aviation navigation and air traffic control communication concepts (adapted from an FAA instrument rating exam; Morrow et al., 2001).

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

Participants also completed several measures related to piloting expertise. All pilots had commercial licenses and were instrument rated (i.e., certified to fly under instrument as well as visual flight conditions). Age was associated with more total flying hours (Y = 6,149 mean hr, M = 17,067, O = 19,193), $F(2, 89) = 35.8$, $\eta^2 = .45$, Y < M = O, but fewer recent hours (Y = 627 mean hr, M = 617, O = 194), $F(2, 89) = 26.0$, $\eta^2 = .37$, Y = M > O. We assessed domain knowledge by using a questionnaire about aviation navigation and ATC communication concepts with 20 multiple-choice items (adapted from an FAA instrument rating exam; test–retest reliability, $r = .79$; Morrow et al., 2001). Of course, pilots outscored nonpilots on this measure (see Table 1). Age had a small but reliable influence ($\eta^2 = .05$) and did not interact with expertise. Thus, although older pilots experienced declines in general cognitive abilities typical of their cohort, on average they had more flying experience than their younger counterparts, and they experienced only small declines on a measure of aviation-related declarative knowledge.

Materials

Navigation chart.—As in the research by Morrow and colleagues (2001), we used a low-altitude en route chart for the northeastern United States airspace with names of navigation reference points changed to make the specific content unfamiliar to pilots. The chart indicated the location of electronic navigational reference points that define standard routes used by commercial aircraft to fly into (approach) or out of (departure) the terminal airspace of surrounding airports. These included radio beacons (VOR, or very-high-frequency omnirange), radials (which radiate off VORs like spokes from a wheel), and Victor airways (part of the low-altitude VOR system that defines standard aircraft routes).

ATC messages.—Participants listened to ATC messages that described four routes through this airspace. There were two waypoint and two vector routes, with presentation order counterbalanced across participants. Each route was accompanied by a flight plan (typed on a 3 in. × 5 in., or 7.5 cm × 12.5 cm, card) indicating a series of VORs, intersections, and connecting Victor airways that identified the intended route (see Figure 1). The route was described by six ATC messages, each corresponding to a leg of the route. Each message began with an aircraft position report (identifying the location and direction of the aircraft when the ATC message is received; this information is not typically part of ATC messages but was necessary for our study) followed by three instructions to change the course of the aircraft, presented in the order specified by the *ATC Handbook* (FAA Order 7110.65): heading, altitude, and speed. As Figure 1 shows, waypoint routes were defined by navigational aids on the chart (on an airway). Instructions were presented in the form of crossing restrictions for position, altitude, and speed instructions (the aircraft was instructed to cross a position in the airspace that was defined relative to a navigational aid such as a VOR or intersection, at a particular altitude and speed). Vector routes, in contrast, were defined by headings that were not anchored to the aids (i.e., off airways). In other words, the vector routes deviated from the original flight plans (to avoid traffic congestion or bad weather). Airline pilots are likely to receive both kinds of route instructions when flying into or out of terminal airspace. All messages were recorded by a retired terminal controller using a speech rate typical of actual ATC operations.

We measured message comprehension by using questions about the aircraft's route. Half of the questions probed the position of the aircraft on the route by asking which of three positions the aircraft would pass closest to if it continued on the assigned course (*position* questions). Some position questions involved computing a projected position from the current aircraft position, which required time/speed calculations that should also be facilitated by environmental support (the chart) in the waypoint condition. The other half of the questions probed the aircraft's assigned altitude by asking which of three other aircraft on the same flight path but at different altitudes would pose a conflict. In other words, if both the participant's aircraft and each of these three aircraft continued on their present course, the participant's aircraft would potentially collide with

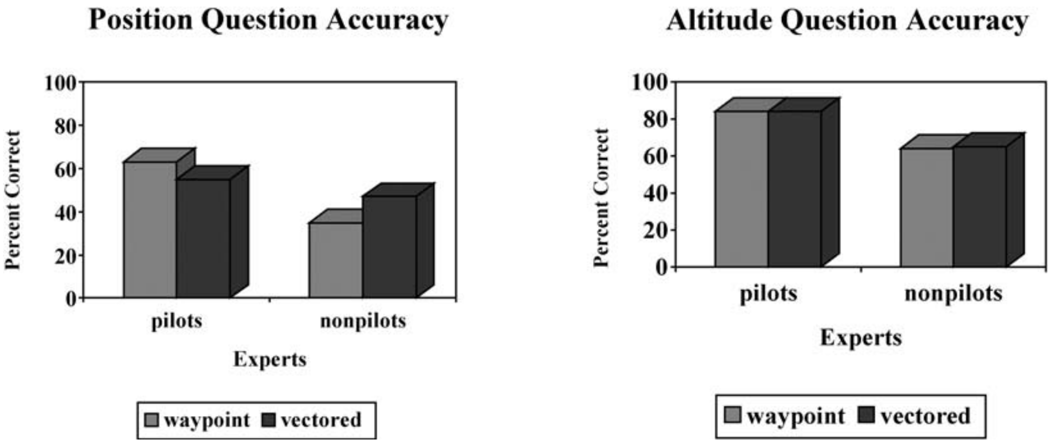

Figure 2. Position and altitude question accuracy, by expertise and route type.

one of the three (*altitude* questions; Figure 1 presents sample position and altitude questions for waypoint and vector routes). Thus, position but not altitude questions required integration of message and chart information.

Procedure

Participants completed the domain knowledge test, followed by training for nonpilots on the aviation tasks (see Morrow et al., 2001, for more detail on training procedure), the aviation tasks, and the domain-general cognitive tasks. For the aviation tasks, participants were first familiarized with the navigation chart. For each route, they reviewed the flight plan for 30 s and then listened to the messages describing the route, with the chart always in view. Participants were not allowed to take notes while listening to the messages. After listening to each message, they read back the instructions and answered a question about aircraft position or altitude (they were instructed to assume that the pilot had responded appropriately to the preceding ATC instructions).

After completing the aviation tasks reported in this article, the participants completed a study that examined the impact of note-taking on readback accuracy (the latter findings are reported as a preliminary study in Morrow, Ridolfo, et al., 2003).

RESULTS

Question Accuracy

We analyzed the mean percentage of correctly answered questions by means of an Expertise (pilot vs nonpilot) 3 Age (Y vs M vs O) 3 Route (waypoint vs vector) 3 Question (position vs altitude) analysis of variance, with the latter two variables as repeated measures. Figure 2 shows that expertise benefits were greater for waypoint than for vector routes for the position questions, suggesting that pilots differentially benefited from the environmental support provided by the chart in the waypoint condition, Expertise 3 Route 3 Question *F*(1, 178) ¼ 4.8, *p* , .05, *MSE* ¼ .096. For position questions, pilots were more accurate in the waypoint versus vector routes, *t*(89) ¼ 2.1, *p* , .05, whereas the opposite held for nonpilots, *t*(94) ¼ 2.5, *p* , .05, Expertise 3 Route *F*(1, 178) ¼ 10.9, *p* , .01. Route type did not affect accuracy of altitude questions (*t* , 1.0 for both pilots and nonpilots).

Altitude questions were answered more accurately than position questions, *F*(1, 178) ¼ 149.6, *p* , .01, *MSE* ¼ .060, presumably because they did not require integration of the message and chart information. Not surprisingly, pilots outperformed nonpilots overall (pilots ¼ 69%, nonpilots ¼ 49%), *F*(1,178) ¼ 59.0, *p* , .01, *MSE* ¼ .098, and younger participants were more accurate than older participants (Y ¼ 65%, M ¼ 60%, O ¼ 54%), *F*(2, 178) ¼ 6.2, *p* , .01. However, support from the chart in the waypoint condition did not mitigate age declines, Expert 3 Age 3 Route 3 Question *F* , 1.0. The Expert 3 Age interaction was also nonsignificant, *F*(2, 178) ¼ 1.6, *p* . .10.

Readback Accuracy

Pilots read back the messages more accurately than nonpilots did (80% vs 54% correct instructions repeated), *F*(1, 180) ¼ 151.6, *p* , .01, *MSE* ¼ .043, and younger participants were more accurate (Y ¼ 75%, M ¼ 69%, O ¼ 59%), *F*(2,180) ¼ 18.3, *p* , .01. Pilots did not differentially benefit from the chart in the waypoint condition (pilots: waypoint ¼ 78%, vector ¼ 83%; nonpilots: waypoint ¼ 50%, vector ¼ 58%), Expertise 3 Route *F*(1, 180) ¼ 2.7, *p* ¼ .10, *MSE* ¼ .011. Rather, both groups read back vector routes more accurately than waypoint routes (71% vs 64%), *F*(1, 180) ¼ 39.9, *p* , .01. This may reflect the fact that the crossing restriction instructions in the waypoint routes were more conceptually complex than the instructions in the vector routes because participants were required to integrate heading or speed with distance and time (i.e., the aircraft needed to be at a specific heading, altitude, or speed at a certain distance from the navigation aid).

Expertise did not mitigate age declines in readback accuracy for waypoint routes, Expertise 3 Age 3 Route *F*(2, 180) ¼ 1.6, *p* . .10. The Expertise 3 Age interaction was also nonsignificant, Expertise 3 Age *F*(2, 180) ¼ 1.2, *p* . .10.

Individual Differences in Aviation Task Performance

We conducted hierarchical regressions to investigate whether performance on the aviation tasks was predicted by individual differences in cognitive ability and expertise, and whether these effects helped explain age differences in performance. Because

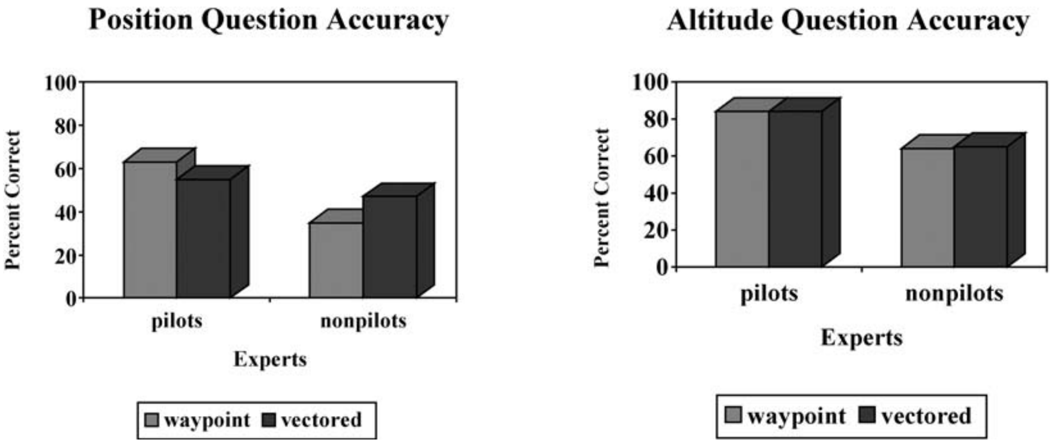

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Table 2. Correlations Among Age, Cognitive Ability and Expertise Measures, and Aviation Task Performance

					Hours		
Variable	Span	Speed	Spatial	Knowledge	Total	Recent	Aviation Perf.
Age	.45***	.60***	.47***	.09	.03	.08**	.32***
Span		.46***	.44***	.21***	.11	.16*	.43***
Speed			.52***	.02	.10	.05	.28***
Spatial				.19	.07	.11	.44***
Knowledge					.79***	.82***	.60***
Total hours						.97***	.59***
Recent hours							.60***

Note: Age is a continuous variable; cognitive ability measures consist of working memory, processing speed, and spatial ability scores; expertise measures consist of domain knowledge and log-transformed total and recent flying hours; and aviation task performance is a composite of question and readback performance. These are given for all participants.

*p , .05; **p , .01; ***p , .001.

performance on the question and readback tasks was correlated (r ¼ .64, p , .001), we conducted the regressions on a composite of the two tasks in order to increase reliability of the findings. Table 2 presents correlations among age, cognitive variables, expertise variables, and the composite aviation task performance variable. We conducted a set of four hierarchical regression analyses. Model 1 examined how much variability in performance was explained by age alone. Model 2 entered the cognitive measures (working memory, processing speed, and spatial ability entered as a block) before age in order to examine how much variability was accounted for by cognitive ability and whether age-related effects were partly explained by individual differences in cognition. Model 3 entered the expertise measures (domain knowledge, and total and recent flying hours) before age. We assigned nonpilots a score of zero for the flight hour measures, and we log-transformed these variables to adjust for the skewed distributions. Controlling for expertise may increase the amount of variability accounted for by age because older pilots had more total flight hours than younger pilots did, which would provide evidence that expertise buffered against age declines (Meinz, 2000). Model 4 examined the impact of expertise and age on performance, with differences in cognitive ability controlled.

Table 3. Hierarchical Regression Analyses Predicting a Composite Readback and Question Accuracy Measure From Cognitive Ability, Expertise, Age, and Expertise 3 Age Interaction Terms

Predictor Variables	% Variance Explained	F	Standardized b	t(1)
Model 1				
Age	9.8	20.7***		
Model 2				
Cognitive scores	24.9	21.0***		
Span			.307	4.1***
Spatial			.316	4.0***
Speed			.030	, 1.0
Age	0.20	, 1.0		
Model 3				
Expertise	39.6	40.3***		
Knowledge			.360	3.6***
Total hours			.016	, 1.0
Recent hours			.293	1.2
Age	12.8***	27.3***		
Model 4				
Cognitive scores	24.9	21.0***		
Span			.307	4.1***
Spatial			.316	4.0***
Speed			.030	, 1.0
Expertise	39.2	39.4***		
Knowledge			.187	1.8[a]
Total hours			.506	2.1*
Recent hours			.033	, 1.0
Age	0.4	1.7		
Expertise 3 Age	1.4	, 1.0		
Knowledge 3 Age			.037	, 1.0
Total hours 3 Age			.254	, 1.0
Recent hours 3 Age			.209	, 1.0

Note: Cognitive ability consists of working memory capacity, processing speed, and spatial ability; expertise consists of log-transformed domain knowledge and total and recent flying hours.

[a] For this value, p , .07.

*p , .05; **p , .01; ***p , .001.

Comparing Models 1 and 2 in Table 3 shows that we eliminated the impact of age when we controlled cognitive ability. Together, the cognitive measures accounted for 24.9% of the variance in performance. The working memory and the spatial ability measures predicted performance, whereas processing speed did not (also see Morrow et al., 2001; Morrow, Menard, et al., 2003). To test whether expertise mediated, or buffered against, age effects, we compared the age-related R^2 in Model 1 to age-related R^2 with total flight hours controlled, because only this expertise measure was positively related to pilot age. This analysis provided some evidence for mediation because age-related variability increased when expertise was controlled (R^2 ¼ 18.0% vs 9.8%).

Model 3 also shows that expertise accounted for almost 40% of the variance in aviation performance. Model 4 shows that, although controlling for cognitive ability did not substantially change the amount of variance explained by expertise, it reduced the betas for the domain knowledge and recent hours measures, perhaps because without cognitive ability controlled the impact of these measures on performance reflects age-related declines in cognition among pilots. Controlling for cognitive ability measures eliminated the effects of age on performance. With cognitive ability controlled (Model 4), higher scores on the domain knowledge test and more total flight hours predicted better performance, as in our earlier studies. Finally, after we controlled for cognitive ability, age, and expertise, the Age 3 Expertise interaction terms were not significant.