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Experience-Based Mitigation of Age-Related Performance Declines: Evidence From Air Traffic Control

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Abstract

Previous research has found age-related deficits in a variety of cognitive processes. However, some studies have demonstrated age-related sparing on tasks where individuals have substantial experience, often attained over many decades. Here, the authors examined whether decades of experience in a fast-paced demanding profession, air traffic control (ATC), would enable older controllers to perform at high levels of proficiency. The authors also investigated whether older controllers would show diminished age-related decrements on domain-relevant cognitive abilities. Both young and old controllers and noncontrollers performed a battery of cognitive and ATC tasks. Results indicate that although high levels of experience can reduce the magnitude of age-related decline on the component processes that underlie complex task performance, this sparing is limited in scope. More important, however, the authors observed experience-based sparing on simulated ATC tasks, with the sparing being most evident on the more complex air traffic control tasks. These results suggest that given substantial experience, older adults may be quite capable of performing at high levels of proficiency on fast-paced demanding real-world tasks. The implications of these findings for global skilled labor shortages are discussed.

Keywords

cognitive aging; human performance; air traffic control; workforce shortage

A consistent observation in the study of aging and cognition is decline in many perceptual and cognitive abilities across the adult life span. Such declines have been observed in both cross-sectional and longitudinal studies across a variety of tasks, abilities, and processes, including measures of perception, working and episodic memory, abstract reasoning, inhibitory processes, multitasking, and spatial abilities (Craik & Salthouse, 2008; Kramer & Willis, 2003; Salthouse, 2006).

Whereas such studies have provided evidence to fuel notions that older is not better, there is another body of literature that has suggested that a byproduct of age is experience, which can be useful for solving complex moral and social problems (Baltes & Staudinger, 1993). Indeed, over the past several decades, researchers have examined whether high levels of experience serve to (a) reduce age-related decline on basic perceptual, cognitive, or motor abilities that presumably underlie complex skills or (b) aid in the development of domain general or specific strategies that can offset or compensate for the impact of aging on complex skills or their component processes (Kramer & Willis, 2003; Morrow, in press). These efforts have met with some success. For example, Charness (1981) found that the effectiveness of search for chess

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moves is unrelated to age for expert players. In the domain of typing, older highly experienced typists perform as well as young professional typists, and this high level of performance for the older typists appears to be due to the more effective use of a preview strategy to offset their slower motor processes (Bosman, 1993; Salthouse, 1984). Masunaga and Horn (2001) used the strategy game GO as a “platform” to investigate age and experience effects. In their study, players of varying age and experience levels were required to perform a series of tasks deemed either relevant or irrelevant to the game. They found evidence of age-related decline on irrelevant tasks and some moderation of age-related differences on the domain-relevant tasks.

Other studies have found equal benefit of expertise for older and younger adults. Age declines in performing standard spatial ability tests are comparable for samples varying in experience on tasks requiring these spatial abilities, either when experience is measured by self-rating (Salthouse et al., 1991) or when novices are compared with professionals whose practice requires these abilities (Salthouse et al., 1990, for architects; Lindenberger, Kleigl, & Baltes, 1992, for graphic designers). Musical expertise does not reduce age differences on music recall (Meinz & Salthouse, 1998) or other music tasks (Halpern, Bartlett, & Dowling, 1995). Knowledge about the topic of a text does not reduce age differences in memory for the text (Hambrick & Engle, 2002; Miller, 2003; Morrow, Leirer, & Altieri, 1992). Although these studies did not find evidence for mitigation, they do suggest that older adults derive the same degree of expertise benefit as younger adults do.

Several studies have also examined experience-based sparing in demanding professions. For example, Tsang and Shaner (1998; see also Tsang & Voss, 1996) investigated the ability of pilots and nonpilots of varying ages to perform a series of single and dual tasks. They found reduced age-related differences on some dual tasks for older pilots but not for nonpilots. However, experience-based mitigation of age-related differences was not found for single task performance. Such a pattern of age-related sparing is not unexpected given the need to frequently time-share and switch between tasks during piloting. Morrow and colleagues have found that older pilots perform similarly to younger pilots on a variety of air traffic communication tasks, particularly when the messages are contextually relevant, when the pilots are permitted to read the messages at their own pace, and when permitted to take notes (Morrow, Leirer, Altiere, & Fitzsimmons, 1994;Morrow, Wickens, Rantanen, Chang, & Marcus, 2008, see also Taylor, Kennedy, Noda, & Yesavage, 2007). Thus, older pilots capitalize on their wealth of domain relevant knowledge to compensate for age-related deficits in working memory.

Although such results are encouraging, these studies have historically investigated and subsequently found evidence of experience-based sparing of abilities that represent only a subset of those needed to succeed in the real world. However, operators managing complex sociotechnical systems must exercise a variety of skills and abilities to maintain optimal performance levels. For example, in aviation, pilots must exhibit sound flight control and navigation ability, in addition to being able to communicate with other pilots and controllers. Hence, observations of experience-based sparing in instances where only a small subset of desired abilities (e.g., communication) are held up to scrutiny (e.g., Morrow et al., 1994, 2003, 2004, 2006) limit the generalizability of such findings.

The need to extrapolate such findings to the real world is pressing. Consider the profession of air traffic control (ATC), which is experiencing severe staffing shortages on a global scale. For example, near misses between aircraft, caused as a result of staffing shortages across Russia, Australia, South Africa, and the United States, are getting close to becoming midair disasters, and in some cases airlines are being forced to choose between cancelling, delaying, or diverting flights, or having loaded jetliners flying through uncontrolled airspace (Baguley, 2008).

Such shortages have been exacerbated by the presence of decades-old mandatory retirement policies that have been established over concerns of age-related performance declines. In the United States, for example, controllers must retire by the age of 56, with numerous studies demonstrating age-related performance declines being cited as justification for enforcing such policies (e.g.,Heil, 1999a, 1999b; Mathews & Cobb, 1974; Trites & Cobb, 1962; VanDeventer & Baxter, 1984). However, these studies have been characterized by (a) reliance on subjective ratings (which can be biased against older adults; see Cobb, 1968) and (b) employment of tasks that often do not reflect operational constraints or afford skilled operators the ability to use strategies acquired over the years. Thus, it is perhaps unsurprising that previous investigations have found limited evidence of success among older adults in ATC.

Evidence of experience-based sparing in such a complex domain has far-reaching implications. Within the ATC context alone, concerns over projected severe controller staffing shortages could be addressed by affording older controllers the opportunity to stay on the job longer. More generally, it may be the case that evidence of experience-based mitigation in a domain such as ATC could provide an indication of the ameliorative benefits that expertise holds as a means of offsetting the detrimental effects of advancing age among operators managing other complex sociotechnical systems (e.g., medicine, construction, industrialized operations).

Present Research

Our study employed older and younger professional air traffic controllers and age-matched noncontrollers who collectively performed a battery of cognitive tasks and simulated ATC tasks that varied in difficulty. The tasks in the cognitive task battery were selected to provide measures of both ATC domain-relevant abilities and less relevant measures of different aspects of cognition (see Wickens, Mavor, & McGee, 1997). Domain-relevant abilities included inhibitory control, task-switching ability, visuospatial ability, working memory, and breadth of attention. Less relevant abilities included processing speed and inductive reasoning. In addition to the cognitive battery, ATC tasks were administered to assess problem-solving ability under different levels of time pressure in a variety of different ATC scenarios. We predicted that, although high levels of experience would do little to ameliorate the detrimental effects of advancing age on cognitive abilities not directly related to ATC, experience would offset potential age-related decrements on those cognitive abilities that are more directly related to ATC as well as on the simulated ATC tasks themselves. More specifically, given the nature of the ATC task, we expected that the abilities of inhibitory or interference control, task switching, visuospatial processing, working memory, and breadth of attention may display some experience-related sparing of aging decrements. On the other hand, we did not expect processing speed or inductive reasoning to show experience-related sparing given that these abilities are less germane to the task of ATC.

In addition to enabling us to examine whether ATC experience influences age-related differences in basic cognitive abilities, the inclusion of the cognitive battery enabled us to address, in part, the “confound of nature” (Morrow, in press) that is inherent in most studies of Experience × Age interactions. That is, because experience tends to increase with age, there is a natural confound in most cross-sectional studies of age and experience (see Hoyer & Ingolfsdottir, 2003, for a rare exception). The cognitive battery enabled us to ask whether the older controllers would outperform the older noncontrollers on a wide variety of cognitive tasks or, as predicted, on only those tasks most closely related to the skills necessary for efficient ATC.

Given that air traffic controllers are generally retired by 56 years of age in the United States, we conducted our study in Canada where controllers can work until 65 years of age.

Method

Participants

Thirty-six licensed ATC controllers and 36 noncontrollers served as participants, with 18 older and 18 younger adults per group. Older controllers (all men) were between the ages of 53 and 64 years (*M* = 57.2), had an operational experience range of between 25 and 38 years (*M* = 34.06), and averaged 1.08 years of postsecondary education. Younger controllers (15 men and 3 women) were between the ages of 20 and 27 years (*M* = 24.4), had an experience range of between 0.25 and 4 years (*M* = 1.64), and averaged 1.65 years of postsecondary education. Controllers were recruited for participation from five different ATC centers across Canada. Older noncontrollers (all men) ranged in age from 52 to 64 years (*M* = 57.5) and had an average of 3.46 years of postsecondary education. Younger noncontrollers (15 men and 3 women) were between the ages of 20 and 27 years (*M* = 23.3) and had an average of 3.82 years of postsecondary education.

Apparatus and Task

Participants completed a series of cognitive and ATC tasks. Within each controller and age group, the order in which the tests from the cognitive and ATC battery were administered was randomized to avoid order effects. The test battery took approximately 6 hr to administer.

Cognitive Test Battery

A number of neuropsychological tests were administered to assess basic cognitive abilities. These abilities and the tests used to measure them are discussed below.

Inhibitory control, which refers to the ability of the individual to suppress responses to objects in the environment that would normally draw attention, was measured using the flanker compatibility task (Lavie & Cox, 1997). Participants complete an easy or hard search task with a compatible or incompatible distractor flanking the search display. The compatibility effect from the distractor item is an index of “spare” attentional resources not used by the search task. In the present task, participants had to determine whether there was a square or diamond among a series of circles, which contained a varying number of shapes (set size manipulation). In addition, a distractor (either a square or a diamond) sometimes appeared outside the array, with participants being told to ignore it and focus on the instructed task. In addition to the practice block, which consisted of 20 trials, the task consisted of 100 trials, with an even split of small versus large set size conditions (50 per condition). Within each half, there was an equal distribution of compatible and incompatible trials (25 per condition). A trial began with a fixation cross presented for 500 ms, followed by the presentation of the stimulus array. Trial administration was self-paced and response time served as the primary dependent variable.

Task switching, which refers to the ability to effectively switch processing priorities between two tasks, was measured using the Trail Making Test (TMT; Army Individual Test battery, 1944). The TMT, and particularly Form B, is considered to be a measure of mental flexibility and task-switching ability. The first portion of the test (Form A) requires the participant to connect circles that contain numbers (1, 2, 3 etc.) in sequence as quickly as possible. The second portion of the test (Form B) is more complex as it requires the participant to alternate between number and letter (1-A, 2-B, etc.) when connecting the circles. The time taken to correctly complete Form B served as our measure of task switching.

Visual spatial processing, which refers to an individual’s ability to process objects and events in space, was measured using the mental rotation task (Cooper & Shepard, 1973). In the present task, a trial consisted of the participant determining whether two shapes presented on the screen were the same or mirror images of one another. The first shape always appeared upright, whereas the second shape appeared at a variety of orientations between 0 and 360 degrees. Following a brief practice, which consisted of 16 trials, the experiment block began, during which 96 trials were administered. The manipulation of shape type (namely, same and different shapes) and orientation (which varied in 45 degree increments between 0 and 335 degrees) was orthogonal, with six trials in each of the 16 different conditions. The trial order was randomized to avoid possible order effects, and response time served as the dependent variable.

Working memory, which entails storage of information, operations on the stored information, and retrieval of information, was measured using the operation span test (Turner & Engle, 1989). Participants were asked to remember words while solving a series of math problems aloud. Following verbalization of a math problem (e.g., IS (5 + 1 = 6?) DOG), the participant had to evaluate whether or not the problem was true and then recite the presented word (in this case *dog*), following which they moved onto the next math problem. In addition to 3 practice problems presented for familiarization purposes, 15 trial problems were administered, each of which varied in length (between two and six) in terms of the number of words that had to be recalled after a given sequence. There were three trials of each sequence size. The experimenter set the pace of the task, and the performance metric used was the number of words that could be accurately recalled in a given sequence (with an all-or-none scoring methodology used).

Breadth of visual attention, which refers to how broadly participants can distribute their visual attention and localize targets in the periphery (Ball, Beard, Roenker, Miller, & Griggs, 1988), was measured using a variant of the useful field of view task. The participant was asked to detect and localize a briefly presented target among a distractor array. A trial started with the target appearing in one of several possible array locations for 40 ms, following by a mask. The participant then used a mouse to click on the region where the target had appeared. The independent variable was the eccentricities of the target from the fixation point, with 10, 20, and 30 degree angles being tested respectively. The experimental session consisted of three blocks of 39 trials, each of which consisted of 13 trials for each of the three different eccentricities tested, and response accuracy served as the performance metric.

Processing speed, defined as the speed at which mental operations can be performed, was measured using the dot comparison task (Salthouse, 1991). Participants compared two nine-dot matrix patterns to determine whether they were identical as quickly as possible, with responses entered via a keyboard. The task was self-paced, with practice consisting of 10 trials; the test comprised three blocks consisting of 36 trials in each block. The patterns that were the same or different were equally distributed across and within blocks, and the time taken to provide a correct response served as the primary dependent variable.

Inductive reasoning, which refers to the ability of an individual to use limited previous experience and observations to make a generalized inference, was measured using the letter series test (Ekstrom, French, & Harmon, 1976). Participants determined the next two letters in a sequence having already viewed the first six letters in the sequence. For example, the sequence A B A C A D would be followed by the sequence A E. Participants had to choose the correct answer from one of four possible options. The test consisted of two parts: the practice portion with 5 practice problems and the experimental portion with 25 problems that got progressively more difficult. Accuracy of the responses served as the performance measure.

ATC Test Battery

Participants also performed a series of ATC tasks. The selection and design of the ATC tasks were based, first, on information acquired during extensive discussions with subject matter experts, who had an aggregated experience of well over 120 years; second, a thorough literature review of task analysis associated with the ATC profession was conducted. The resulting set of ATC tasks included conflict detection, conflict resolution, vectoring, and airspace management. On each task, practice trials were administered to minimize observable learning effects during the data collection phase of testing.

Conflict detection task—In this basic ATC task, participants made perceptual judgments as to whether two aircraft on a given trial would conflict with one another at some future point. A trial began with two aircraft converging toward one another at the same altitude on the radar screen. The position of each aircraft was updated once every 6 s (which is the approximate update rate for current radar systems), and geometries and speeds at which the aircraft converged varied from one trial to the next (Figure 1a). Task difficulty was manipulated by varying the time to the closest point of approach, with increases in time making perceptual judgments more difficult given the larger distances generally involved. Trial type (conflict present trials vs. conflict absent trials) was also manipulated, and the time taken to arrive at a correct decision served as the dependent variable. The manipulation of conflict presence and time to the closest point of approach was orthogonal, with 20 trials in each condition for a total of 120 trials. Trial order was randomized across participants to avoid order effects, and the task took approximately 40 min to complete.

Conflict resolution task—A more complicated variant of the conflict detection task was the conflict resolution task in which participants' problem-solving capability was measured by having them resolve a series of complex ATC problems. More specifically, conflicts between aircraft pairs on a collision course had to be resolved by issuing altitude guidance instructions via a control interface (Figure 2a). The time to conflict, defined as the time taken by the aircraft to reach the conflict point, was manipulated; the time taken to correctly resolve the conflict served as the primary dependent variable. There were a total of 30 trials in this phase, with 10 trials for each of the three time-to-conflict conditions. Once again, the order in which the trials were administered was randomized across participants, and the task took approximately 45 min to complete.

Vectoring task—The first of two full dynamic simulation tasks, the vectoring task required participants to navigate aircraft approaching an entry point, ensuring they stayed within a specified boundary of airspace and reached their final waypoint without being in conflict with any other aircraft (Figure 3a). The radar screen depicted a sector of airspace 60 × 60 miles; all aircraft had a data tag that depicted the aircraft's altitude and speed, and the heading of the aircraft could be inferred from its vector line (which depicts the projected aircraft path). The task, which was designed to mimic traffic flows at an approach control facility, required a high degree of interaction (manual input) with the computer to ensure that sector rules were followed. Aircraft approaching from the west always entered the sector at FL 350 and had to descend to FL 330 before a specified point. Conversely, aircraft approaching from the east entered at FL 320 and had to descend to FL 310 before exiting the sector. For a typical handling sequence, the participant had to first accept the aircraft into the sector, issue the altitude and heading commands when appropriate to ensure minimal deviation from the route, and finally hand off the aircraft to the next sector. These commands were issued to the aircraft via the flight control interface that was available to the participant when needed by pressing the right mouse button. The main independent variable that was manipulated was airspace load. Under low load, aircraft entered the sector at a rate of one aircraft every 90 s. Under high load, the time interval was reduced to once every 60 s. Aircraft entry at the waypoints was alternated so that if an aircraft appeared at the eastern entry fix at the onset of the simulation, the next aircraft would appear at the western fix. The primary performance metric was the aircraft-handling capacity, defined as the number of times aircraft successfully passed through their assigned waypoint based on issuance of correct control instructions by the participant. Performance was assessed over the course of the "shift," which lasted approximately 45 min.

During the initial briefing for the vectoring task, participants became familiar with the interface and simulation platform and performed the task under varying aircraft entry rates. Practice lasted approximately 20 min. During the experimental phase, participants handled 14 aircraft under low-load and 14 aircraft under high-load conditions (with each aircraft serving as a trial). Given that the aircraft entry rate was related to airspace load, under low load, the scenario lasted approximate 30 min, and the high-load phase lasted approximately 12 min. The order in which airspace load was experienced by participants was always fixed, with low load administered first, followed by high load.

Airspace management task—A more complicated variant of the vectoring task and the most complex task in the ATC battery, the airspace management task required participants to manage the flow of traffic along different airways through a specified sector of high-altitude airspace (Figure 4a), which was approximately 150 × 150 nautical miles. To do so, aircraft first had to be accepted into the sector, and their flight paths had to be checked to ascertain which route they were required to traverse. Following determination of the route, the participant had to ascertain the altitude restrictions associated with that route, coupled with determinations of heading commands required to keep the aircraft along the route. This information could be obtained by checking visual reference markers and each aircraft's data tag (which depicted the call sign and altitude and speed assignments) on the radar screen. The participant was solely responsible for issuing all the altitude, heading, and speed assignments (via the flight control interface) necessary to get the aircraft safely from its entry point to its exit point. The final task included handing off the aircraft to the next sector controller when it approached the final waypoint along its route. Task difficulty was manipulated by varying the entry rate of aircraft into the sector, resulting in low and high airspace load. Under low load, a total of 10 aircraft entered the sector in 30 min; under high load, 20 aircraft entered the sector. As was the case in the vectoring experiment, low load always preceded high load. Performance measures included the number of commands issued to manage the airspace, the number of operational errors that occurred, and aircraft-handling capacity during the "shift," which lasted approximately 60 min.

The task familiarization for the airspace management task took approximately 15 min, coupled with another 30-min practice session. Following this, the experimental phase began, with participants managing the traffic flow for 60 min (30 min under low load and 30 min under high load), after which the simulation terminated.

ATC task battery realism—The ATC battery was developed in consultation with our subject matter experts to place participants in as realistic an ATC environment as possible given logistical constraints. Each task in the battery had participants rely on their visuospatial, problem-solving, and task management abilities to attain optimal performance levels, requirements that are not unlike those demanded in the current ATC environment. We acknowledge the absence of additional characteristics in our more complex ATC tasks (such as voice communication, issuance of weather advisories, and physical receipt and handoff of flight strips) whose inclusion may have improved the overall ATC experience.

However, there were two reasons why such characteristics were omitted. First, we sought to achieve a balance between placing participants in an environment that was realistic enough so that the mitigating effects of experience could be observed among controllers (Craik & Jennings, 1992; Kirlik, 1995) but did not impede the conduct of the data collection process given logistical constraints. For example, given that data were collected at a number of facilities, access to the same group of pilots for experimental control purposes would have been difficult. Second and more important, given that the inexperienced controller group had no prior ATC knowledge, it was important to simplify the ATC task sufficiently so that it could be performed by this group while ensuring that benefits of prior controller training would also be evident across the range of tasks.

Procedure

All participants were first prescreened to ensure that they were in good health, following which they were assigned to their respective age and experience groups. Half of the participants in each of the four Age × Experience groups received the ATC battery first, and the remaining half received the cognitive battery first. Within each group, the order in which the tests were administered was randomized to avoid order effects. The ATC and cognitive test batteries were administered on separate days to avoid fatigue. Because of scheduling constraints, time of day was not accounted for during testing. Finally, given that the entire experiment was expected to take approximately 8 hr, regular breaks were offered to participants.

Results and Discussion

In this section, we begin with the analyses of the tasks from the cognitive battery to determine whether, and to what extent, high levels of experience on air traffic control served to reduce age-related decline on tests of different perceptual and cognitive abilities. We then examine whether, in the face of age-related declines on basic cognitive abilities, older controllers were able to maintain high levels of performance on a variety of increasingly more complex and difficult ATC tasks. Means and standard errors for different cognitive battery task conditions are presented in Tables 1 through 4. Because of space limitations, analysis of variance tables (Tables 5–13) have been included as an online supplement.

Influence of Experience on Cognitive Abilities

Data from the cognitive test battery (Tables 1-4) were analyzed with mixed-mode analyses of variance (ANOVAs).[1] In this article, we focus on the Age × Experience interactions because these effects are most relevant to our hypotheses. The analyses of the tasks in the cognitive battery revealed age-related declines for both controllers and noncontrollers on all of the tasks, with evidence of experience-based sparing on only two (inhibitory control and visuospatial) of the seven abilities investigated. On these two abilities, a significant interaction was observed between experience and age, with a smaller age-related difference in cognition between the young and older controllers than between the young and old noncontrollers. More specifically, we found that on the flanker task (see Tables 1 and 5), experience moderated the incompatibility effect among older participants when the set size was small but not when the set size was large, $F(1, 68) = 6.26$, $\eta^2 = .33$, $p < .01$. Larger compatibility effects are often reported with smaller set sizes (Forster & Lavie, 2008). Therefore, the smaller set size compatibility effects should be more sensitive to age and experience than larger set size conditions. Similarly, we also observed that on the mental rotation task (see Tables 2 and 7), experience reduced the age difference in response time to mentally rotate geometric shapes for controllers compared with noncontrollers, $F(1, 68) = 3.32$, $\eta^2 = .03$, $p < .01$. The accuracies for the flanker and mental rotation tasks were high and consistent with the response time data.

Consistent with our hypotheses, both inhibitory control and visuospatial processing showed experience-based sparing for the older controllers. Also consistent with our hypotheses, based on an analysis of the ATC task, no experience-based sparing was obtained for measures of processing speed, $F(1, 68) = 0.01$, $\eta^2 = .00$, $p > .96$, or inductive reasoning, $F(1, 68) = 0.03$,

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[1] We did not perform a MANOVA with the cognitive battery tasks as we did with the ATC battery tasks. Given the number of factors in the tasks employed in the cognitive battery, it was impossible to simplify the variables such that they would make sense in a MANOVA. However, this is much less of a concern for the cognitive battery given that few of the tasks should have significant Age × Experience interactions.

$\eta^2 = .00$, $p > .87$. On the other hand, three other abilities that would appear to be relevant to ATC—namely, task switching, $F(1, 68) = 0.03$, $\eta^2 = .01$, $p > .56$, working memory, $F(1, 68) = 3.09$, $\eta^2 = .04$, $p > .08$, and breadth of attention, $F(1, 68) = 1.06$, $\eta^2 = .02$, $p > .31$— did not display evidence of experience-based sparing. It is certainly conceivable that after many years of serving as an air traffic controller, the ATC task-switching task becomes unitized and highly integrated (Kramer, Hahn, & Gopher, 1999; Kramer, Wickens, & Donchin, 1985; Logan, 2005), therefore, reducing the necessity to switch attention among different subcomponents of the ATC task. Similarly, in examining working memory, it may well be the case that experienced controllers rely less on internal capacity limited storage and more on external information (e.g., flight progress strips, radar) to maintain the "picture" of the overall traffic situation. With regard to the breadth of attention, it is possible that controllers sequentially focus attention on specific aircraft rather than processing information concerning multiple aircraft in parallel (as would be consistent with the construct of breadth of attention). In any event, the results for the cognitive battery suggest, consistent with the extant literature (Morrow, in press; Salthouse, 1984), that experience gained in specific professions or other pursuits, often over the span of several decades, tends to have rather limited effects on only the most domainrelevant cognitive abilities. That is, high levels of experience do not broadly provide immunity against the detrimental effects of advancing age on basic cognitive functioning.

Experience and Performance on Simulated ATC Tasks

A multivariate analysis of variance (MANOVA) was conducted on measures from each of the four ATC tasks to determine whether experienced-based age-related sparing would be observed. Significant main effects were obtained for age, $F(1, 65) = 28.6$, $\eta^2 = .64$, $p < .01$, and experience, $F(1, 6) = 22.4$, $\eta^2 = .58$, $p < .01$, as well as for the Age × Experience interaction, $F(1, 68) = 7.6$, $\eta^2 = .32$, $p < .01$. Therefore, this analysis was followed by ANOVAs for each of the four ATC tasks.

Older controllers performed quite well on the ATC task, with results from the ATC battery being more consistent with the experience-based sparing hypothesis. That is, experience-based sparing increased with increasing complexity of the ATC tasks. The results (Table 10, Figure 1b) from the relatively simple conflict detection task yielded no evidence of experience-based sparing, $F(1, 68) = 0.01$, $\eta^2 = .00$, $p > .92$. However, the age-related performance decrement on the conflict resolution response task (Table 11, Figure 2b) was significantly smaller among controllers compared with noncontrollers, $F(1, 68) = 4.66$, $\eta^2 = .03$, $p < .03$, suggesting that in comparison to low-level perceptual tasks, the benefits of experience-based mitigation may be more evident on more difficult problem-solving tasks.

The vectoring task represented a more dynamic environment where decisions had to be made and actions enacted under greater time pressure. Here we observed (Table 12, Figure 3b) that, once again, high levels of experience ameliorated the effects of age-related performance declines, $F(1, 68) = 27.01$, $\eta^2 = .14$, $p < .01$. More specifically, we found no difference in aircraft-handling capacity for the young and older controllers. However, this was not the case for the younger and older noncontrollers. Furthermore, age-related performance differences increased with increased traffic for the noncontrollers but not for the controllers.

The airspace management task, which represented the most complex and realistic ATC environment, also supported the experience-based sparing hypothesis. Our analysis (see Table 13) showed that whereas a frequency analysis of control inputs (a quantitative metric) revealed that both the type and ratio of command instructions (altitude, heading, and speed) issued by older and younger controllers were similar, the number of control inputs on the radar screen by older controllers was lower than that of younger controllers (Figure 4b). This is noteworthy because analysis of our qualitative measures, such as operational error rate (Figure 4c) and aircraft handling capacity (Figure 4d), revealed few differences in performance between older and younger controllers. This suggests that younger controllers may be issuing more commands than are necessary compared with the older controllers, who issue fewer commands while achieving the same results. Such results are noteworthy because they suggest that older controllers can compensate for reductions in cognitive ability by acting in a more measured fashion to achieve performance that rivals that of their younger counterparts who exhibited better cognitive ability.

We note that similar effects were absent for the noncontroller group, where significant age-related performance impairments were observed. These data suggest that in the face of age-related decline across many basic cognitive abilities, seasoned older professionals may use alternative strategies (Backman & Dixon, 1992) that employ domain-relevant knowledge to efficiently manage complex sociotechnical systems. We also note a trade-off between error rates and aircraft-handling capacity in the noncontroller group: More specifically, younger noncontrollers appear to have handled a higher aircraft volume at the expense of a greater error rate.

In collectively viewing the results from the ATC task battery, it is important to note that evidence of experience-based mitigation was observed on three of the four ATC tasks administered (the only exception being the conflict detection task). In addition, inspection of the conflict error data on the most complex task (Figure 4c), the airspace management task, revealed little difference in performance between younger and older controllers. This effect is noteworthy given longstanding arguments that have postulated that performance lapses are more likely to be exhibited by older controllers, this given their declining cognitive abilities (although we note that recent analysis of operational data by Broach and Schroeder, 2006, has also revealed little evidence of age-related differences in operational error rates among controllers).

Indeed, many of these arguments have been used as the basis for establishing and maintaining current mandatory retirement practices in the ATC domain. Our results, however, suggest that older controllers are able to reduce their susceptibility to the detrimental effects of age by relying on domain-specific experience. Moreover, in examining performance on the conflict detection, conflict resolution, vectoring, and the airspace management task, it appears that the experience benefit was manifested in a clearer fashion (as evidenced particularly by an equivalent conflict error rate between older and younger controllers on the airspace management task). The conflict detection task represented a low-level perceptual task that was not very complex. The conflict resolution task provided controllers with the chance to generate their own solutions while taking safety and efficiency measures into consideration. The vectoring task provided controllers with a more dynamic environment in which aircraft sequencing could be done; finally, the airspace management task afforded controllers to vector aircraft, change altitudes, and shed subtasks, affordances that are not unlike the environment in which they currently operate. Hence, it appears that when placed in an increasingly complex environment, superior performance by older controllers may be due to greater reliance on experience that is most useful in a realistic environment and whose mitigating effects are most likely to be evident when the task supports use of that knowledge (Craik & Jennings, 1992; Kirlik, 1995). Our findings are congruent with the supposition of researchers (Abernathy & Hamm, 1995; Chase & Simon, 1973; Gilhooly, Wood, Kinnear, & Green, 1988; Vicente, 1992) who have proposed that experts will outperform novices when information is organized in terms of domain principles, as it was in the current study.

It is important to note that age and experience were confounded with one another in the controller group, which can usually make it difficult to isolate their additive and interactive effects. It is for this reason that participants with no air traffic experience were included in the study, effectively providing a “control” and enabling us to isolate the relative contributions of age and experience independent of one another. Indeed, here we observe that although age-related performance impairments were evident across both cognitive and ATC tasks among older participants, the substantially larger age effect observed for noncontrollers compared with controllers attests to the benefits of domain-specific experience. We also acknowledge that the use of a longitudinal design would have afforded us the opportunity to control for selective attrition effects. However, given the logistical constraints (e.g., extensive timelines for obtaining relevant data sets) associated with the conduct of such a study, this is not possible in most studies of Experience × Age interactions. Nevertheless, we do believe that the present results provide accurate information regarding the benefits of experience (this given that a subset of the results has been observed in previous empirical studies) and that these results are timely. However, we acknowledge that our findings should be supplemented by follow-on research efforts that employ longitudinal techniques as a means of providing converging evidence to support or refute the results presented here.

Another point that warrants discussion is the observation that younger noncontrollers performed as well as younger and older controllers on the ATC task battery. Although such an effect could call into question whether or not such tasks actually require ATC expertise, we note that the task battery was developed in close consultation with professional controllers and, more important, that the battery was sensitive enough to detect performance variations among controllers as a function of task complexity (with the most pronounced effects being observed as the tasks got more and more complex). Hence, we assert that the ecological validity of the battery is sound and that ATC expertise is required to achieve optimal performance, particularly on the most challenging tasks.

A more plausible reason for our finding could be that, given that the experience of interacting with the ATC simulation platform is analogous to playing an interactive video game, younger inexperienced adults are much better suited for such tasks compared with their older counterparts, considering their greater familiarity with playing video games on a day-to-day basis. Indeed, similar effects have been observed in previous empirical work (Gopher, Weil, & Siegel, 1989). This may well explain why younger noncontrollers were able to achieve performance levels equivalent to those of their experienced counterparts on a subset of tasks in the ATC battery. It may be the case that immersion into a full-scope ATC environment (that demands voice communication, physical coordination, and strip handling with other controllers) would better help illustrate the benefits of ATC-specific expertise when performing tasks administered in the ATC battery.

A related concern that we wish to address is that older noncontrollers may have been less computer literate that their experienced and inexperienced counterparts, an effect that may create uncertainty in interpreting the observed Age × Experience interactions. Although this is certainly plausible, we note that older noncontrollers had twice the amount of formal education as their experienced counterparts (3.46 compared with 1.08 years) and were working professionals. As a result, there is little reason to suspect that computer literacy may have been a factor, which affected complex task performance among older noncontrollers.

In sum, we may draw a number of conclusions from these results. First, from a theoretical standpoint, experience appears to moderate the effects of age-related decline on only a subset of the most relevant of cognitive abilities that underlie complex task performance. Second, the magnitude of experience benefits appears to be largely a result of the knowledge older workers use to mitigate the impact of age-related cognitive decrements as task complexity increases. Third, our results suggest that mandatory retirement policies introduced several decades ago to ensure safety across myriad complex professions should perhaps be reexamined. We note that in the ATC domain at least, the present set of data provides countries faced with controller shortages (e.g., United Stastes, Russia, South Africa, and Australia) with one avenue for dealing with this issue and that our findings are congruent with recent field study analysis (Broach & Schroeder, 2006), which has revealed little evidence of age-related performance impairments between older and younger operators.

Given that the world's population is ageing rapidly (Andreev & Vaupel, 2005; U.S. Census Bureau, 2004), the current results suggesting that older workers are capable of managing complex sociotechnical systems independent of chronological age (at least within the age ranges examined here) should provide a staffing solution (albeit temporary) in domains where skilled labor shortages are likely to be observed, such as ATC (Baguley, 2008; Becker & Milke, 1998). Moreover, there is also reason to be optimistic that the current evidence of older worker success in a domain as complex as ATC may be somewhat indicative of the potential older workers possess in successfully managing other complex sociotechnical systems (e.g., medical, construction, and electrical industry, where similar shortages are being faced). From a social perspective, however, harnessing the capital offered by these workers will depend on not only our ability to overcome traditional age-related stereotypes, but also on embracing the philosophy that workers should get and keep jobs on the basis of their ability, not their age.

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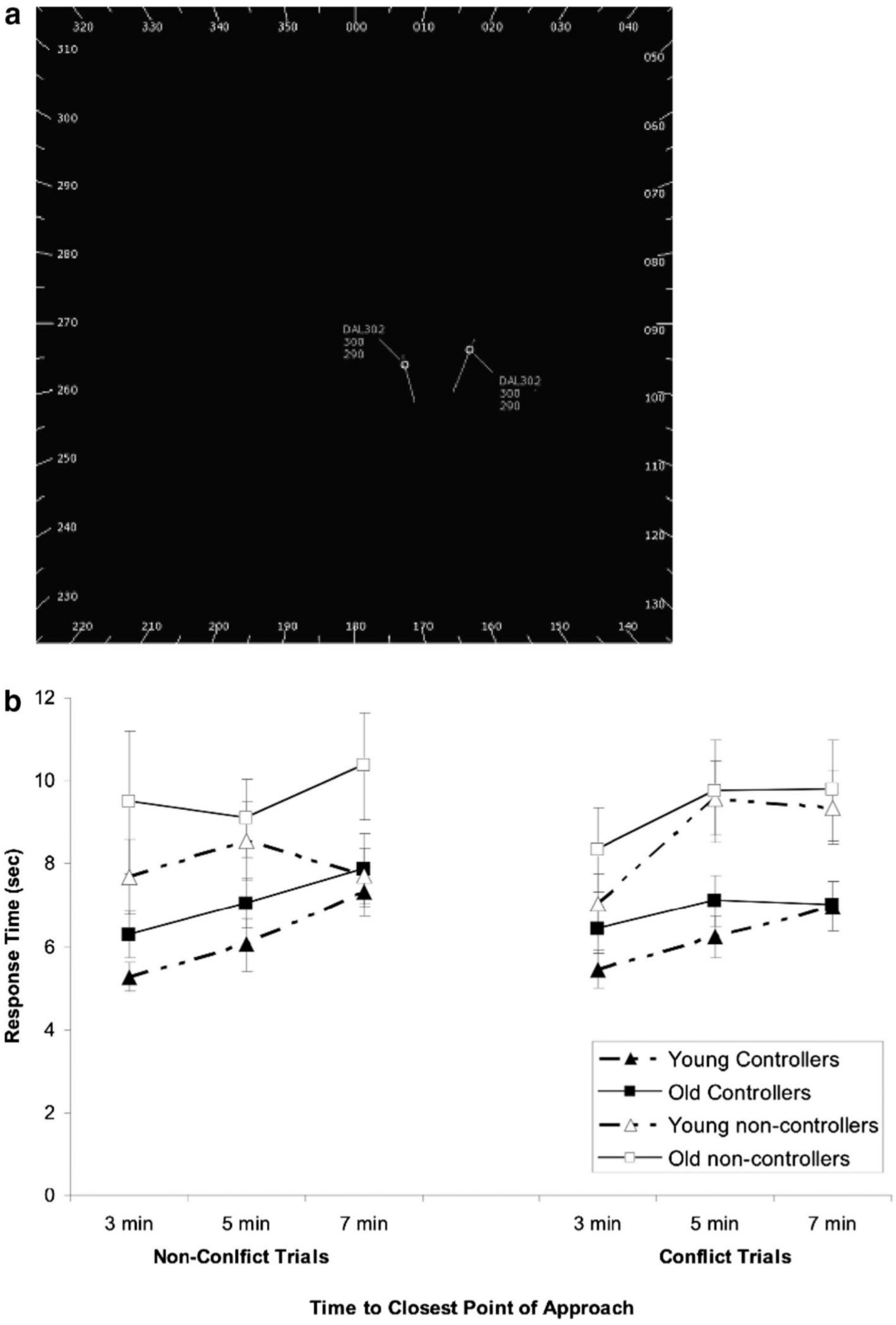


Figure 1.

(a) The conflict detect task: Participants are asked to render simple conflict or nonconflict judgments regarding aircraft pairs converging toward one another. Of interest is the amount of time taken to safely and correctly render a decision. (b) On this basic task, there is no evidence to support the experience-based sparing hypothesis.

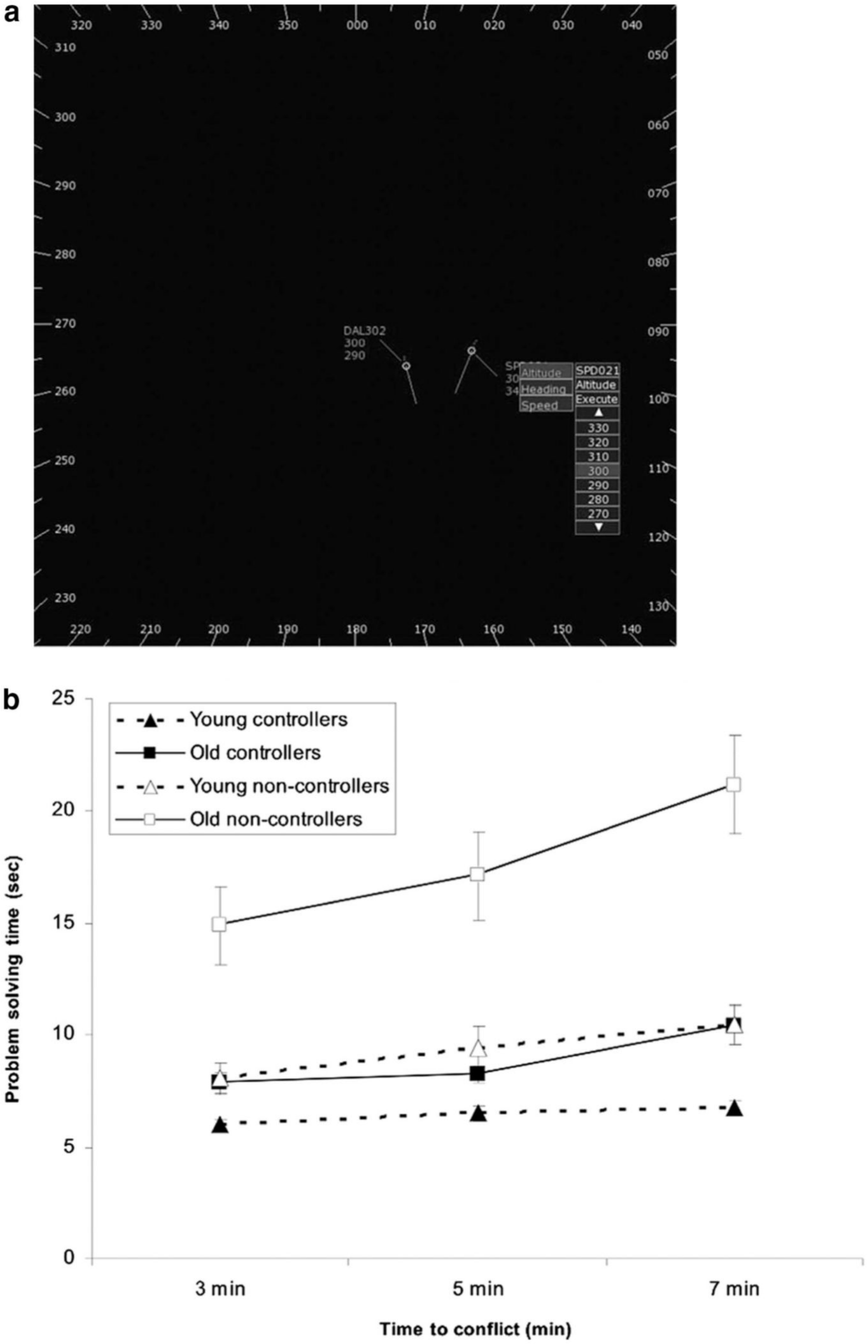
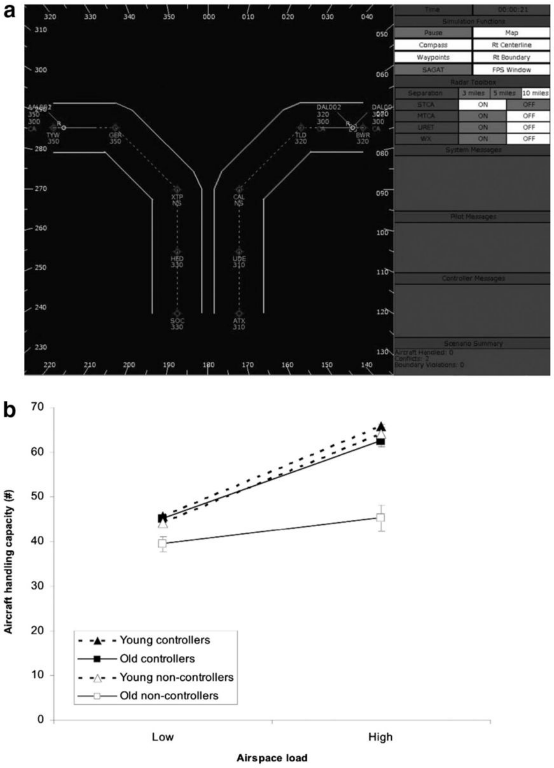


Figure 2.

(a) The conflict resolution task: Participants are asked to resolve potential conflicts between aircraft pairs by issuing guidance control instructions. Given the limits of human perceptual ability, the task becomes increasing difficult as participant responses are sought farther from the potential conflict point. Of interest is the amount of time taken to safely resolve the conflict. (b) We observed that the magnitude of age-related performance decrement was higher among noncontrollers than that among controllers, providing evidence for the experience-related sparing hypothesis.



Aircraft Handled: 0
Conflicts: 2
Boundary Violations: 0

Figure 3.

(a) The vectoring task in which participants must sequence aircraft along two air corridors around an airport. The task becomes increasingly challenging as airspace load increases. (b) A significant interaction is observed between experience and age, with no difference in performance between more and less experienced controllers but a substantial difference in aircraft-handling performance between young and older noncontrollers.

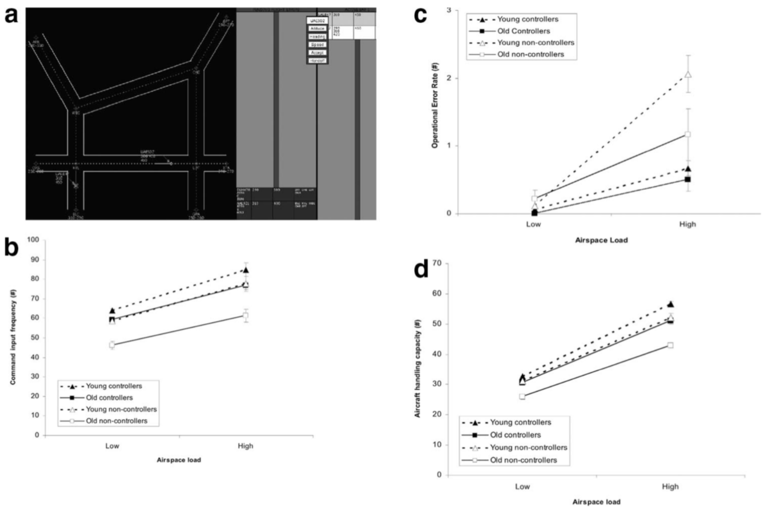


Figure 4.

(a) The airspace management task: Participants are asked to manage the flow of aircraft through a region of airspace under increasing traffic load. (b) Results show that older noncontrollers issue fewer guidance control instructions than younger controllers. (c) Closer analysis of the operational error rates also reveals equivalent performance between older and younger controllers, suggesting that compensatory strategies are used by the former group to maintain optimal performance levels. (d) This is noteworthy because the number of aircraft handled by older and younger controllers is nearly equal, this given that an aircraft passes through an average of four waypoints to reach its destination, which means that younger controllers handled an extra 1.5 aircraft in comparison to older controllers.

Table 1

Mean Response Times (ms) for the Inhibitory Functioning (Flanker) Task

	Flanker			
	Small set		**Large set**	
Group	**Compatible**	**Incompatible**	**Compatible**	**Incompatible**
Young controllers	630.67 (17.01)	642.61 (17.42)	965.81 (36.01)	966.19 (31.17)
Old controllers	835.58 (34.55)	837.22 (34.17)	1424.03 (56.99)	1454.58 (62.05)
Young noncontrollers	670.39 (38.89)	688.97 (45.92)	1039.33 (57.25)	1042.17 (55.16)
Old Noncontrollers	821.08 (31.55)	924.53 (66.18)	1501.31 (56.24)	1483.56 (63.29)

Note. Standard errors appear within parentheses.

Table 2

Mean Response Times (ms) for the Visuospatial Task

	Mental rotation (degrees)							
Rotation angel/group	**360**	**45**	**90**	**135**	**180**	**225**	**270**	**315**
Mirror shape								
Young controllers	1057.1 (62.6)	1423.2 (79.4)	1624 (64.3)	1630.5 (91.2)	1783.9 (89.7)	1775.6 (79.8)	1636.4 (81.3)	1383.5 (79.4)
Old controllers	2128.5 (283.1)	2329.7 (279.1)	2432.7 (259.3)	2418.7 (183.7)	2889.4 (281.4)	2549.6 (266.7)	2648.4 (363.3)	2276.1 (261.2)
Young noncontrollers	1076.4 (70.3)	1335.8 (106.9)	1584.6 (116.7)	1612.3 (127.1)	1759.2 (111.2)	1709.2 (128.3)	1688/1 (108.8)	1340.7 (89.2)
Old noncontrollers	2207.4 (194.5)	2467.2 (279.7)	2712.3 (190.9)	2745.6 (226.6)	2821.4 (164.3)	2700.6 (154.7)	2544.8 (145.7)	2174.1 (188.7)
Same shape								
Young controllers	853.6 (27.6)	1108.1 (45.9)	1317.3 (37.2)	1415.1 (66.6)	1790.9 (103.0)	1749.6 (82.4)	1507.1 (64.9)	1155.9 (33.9)
Old controllers	1532.2 (179.2)	1682.4 (135.5)	2081.6 (140.1)	2333.8 (286.2)	2903.5 (433.4)	2643.4 (243.1)	2326.8 (226.3)	1874.5 (143.5)
Young noncontrollers	883.5 (43.8)	1079.2 (41.8)	1606.4 (147.8)	1482.6 (81.3)	1742.0 (125.8)	1596.9 (90.5)	1448.5 (83.9)	1086.6 (44.8)
Old noncontrollers	1627.2 (116.7)	1901.3 (188.9)	2256.3 (163.7)	2358.8 (215.6)	2812.4 (220.3)	3028.9 (245.4)	2581.6 (206.8)	2268.4 (167.5)

Note. Standard errors appear within parentheses.

Table 3
Mean Accuracies for the Breadth of Attention Task

	Useful field of view (eccentricity, degrees)		
Group	**10**	**20**	**30**
Young controllers	0.92 (.05)	0.87 (.05)	0.79 (.06)
Old controllers	0.60 (.06)	0.53 (.05)	0.45 (.05)
Young noncontrollers	0.93 (.03)	0.90 (.05)	0.83 (.04)
Old noncontrollers	0.51 (.06)	0.45 (.05)	0.39 (.04)

Note. Standard errors appear within parentheses.

Table 4

Summary of Means for the Working Memory, Processing Speed, Inductive Reasoning, and Task-Switching Tasks

Group	Working memory: Operation span (no. words)	Processing speed: Dot comparison (ms)	Inductive reasoning: Letter series (%)	Task switching	
				Trail making A (s)	Trail making B (s)
Young controllers	16.44 (1.36)	1645.53 (56.83)	0.87 (0.02)	21.92 (1.36)	25.50 (1.95)
Old controllers	13.94 (1.87)	2319.08 (64.17)	0.71 (0.04)	30.34 (1.77)	35.28 (1.87)
Young noncontrollers	23.88 (5.74)	1678.07 (86.23)	0.87 (0.02)	42.08 (1.45)	47.37 (2.68)
Old noncontrollers	14.31 (3.37)	2379.94 (107.32)	0.71 (0.03)	62.84 (4.88)	76.42 (5.17)

Note. Standard errors appear within parentheses.