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The impact of brain size on pilot performance varies with aviation training and years of education

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Abstract

Previous studies have consistently reported age-related changes in cognitive abilities and brain structure. Previous studies also suggest compensatory roles for specialized training, skill, and years of education in the age-related decline of cognitive function. The Stanford/VA Aviation Study examines the influence of specialized training and skill level (expertise) on age-related changes in cognition and brain structure. This preliminary report examines the effect of aviation expertise, years of education, age, and brain size on flight simulator performance in pilots aged 45–68 years. Fifty-one pilots were studied with structural magnetic resonance imaging, flight simulator, and processing speed tasks. There were significant main effects of age ($p < .01$) and expertise ($p < .01$), but not of whole brain size ($p > .1$) or education ($p > .1$), on flight simulator performance. However, even though age and brain size were correlated ($r = -0.41$), age differences in flight simulator performance were not explained by brain size. Both aviation expertise and education were involved in an interaction with brain size in predicting flight simulator performance ($p < .05$). These results point to the importance of examining measures of expertise and their interactions to assess age-related cognitive changes.

Keywords

Magnetic resonance imaging; Aptitude; Motor skills; Age; Neuropsychological tests; Occupations

Introduction

The hallmarks of normal aging include a decline in a range of cognitive abilities such as executive functioning (Moscovitch & Winocur, 1992; West, 1996), working memory (Baddeley, 1986), processing speed (Salthouse, 1996; Schaie, 1989), and episodic and semantic memory (Luszcz, Bryan, & Kent, 1997). Age-related changes in brain structure, especially in the prefrontal and medial temporal lobe regions, have been associated with decline in these cognitive abilities (Greenwood, 2007; Raz et al., 2005; Sullivan, Rohlfing, & Pfefferbaum, 2010). On the other hand, animal studies show that a stimulating environment can increase synaptic density and complex cortical connections (Richards & Deary, 2005). In human aging

research, literacy, education, and occupational level are traditionally used as markers for providing a stimulating environment that may offer protection against the deleterious effects of aging (Richards & Deary, 2005; Stern, 2006). For example, education has been associated with slower decline of memory and executive function task performance in healthy older individuals (Le Carret, Lafont, Mayo, & Fabrigoule, 2003; Manly, Schupf, Tang, & Stern, 2005; Stern, 2006). Education has also been found to be a protective factor against converting to mild cognitive impairment (Bennett et al., 2003; Bruandet et al., 2008; Dufouil, Alperovitch, & Tzourio, 2003) and developing severe white matter hyperintensities (Dufouil et al., 2003). Despite declines in basic cognitive abilities and brain size, older adults can also improve their performance on certain tasks by skill learning or specialized training (Baltes & Kliegl, 1992). Some of the most notable studies, recently reviewed in Stern (2009) and Hertzog, Kramer, Wilson, and Lindenberger (2009) attest to this improvement in specific trained skills in older adults. Studies investigating a range of occupationally relevant tasks such as typing, piano playing, and aviation simulations show that older experts can often, although not always, perform as well as younger experts, despite evidence of age-related declines in basic cognitive, perceptual, or motor abilities (Jastrzembski, Charness, & Vasyukova, 2006; Richards & Deary, 2005; Stern, 2006). Therefore, in addition to education and/or literacy, expertise and specialized training can also serve as protective factors that may modulate the course of performance declines.

The Stanford/VA aviation cohort provides a unique opportunity to directly observe the influence of a standardized and monitored level of aviation expertise on flight simulator performance. Moreover, flying a plane is a complex cognitive task and likely involves several regions of the brain. We, therefore, investigated the effects of head size-adjusted whole brain volume, along with aviation expertise, education, and age on performance in a complex task such as flying a plane. Our analytic approach is similar to how Salthouse (1996) used processing speed, an ability that is correlated with age, as the mediating factor between age and task performance. By using this approach, we hope to tease apart the roles of age, aviation expertise, and brain size on complex skilled performance.

Figure 1 illustrates how three independent variables in the current study—age, aviation expertise, and brain size—may theoretically influence flight simulator performance. Brain size may influence flight simulator performance directly and/or may also mediate some of the effects of age on flight simulator performance. First, as discussed above, age can exert a deleterious effect on brain size and flight simulator performance. Second, aviation expertise may alter the relationship between brain size and flight simulator performance. To systematically tease apart the independent variables in this study, we will follow the Baron and Kenny (1986) criteria for mediator and moderators, see also (Kraemer, Kiernan, Essex, & Kupfer, 2008). Essentially, a mediator is defined as an intermediate variable that functions as a mechanism by which an independent variable exerts its influence on a dependent variable. For this relationship to exist, several conditions must be met: (1) the independent variable and the dependent variable must be significantly correlated, (2) the independent variable must be correlated with the mediator, (3) the mediator affects the dependent variable, and (4) the effect of the independent variable on the dependent variable is reduced or eliminated when the mediator is controlled.

A moderator, on the other hand, is defined as that independent variable that influences the association between another independent variable and the dependent variable, without influencing that independent variable directly (usually assessed by an interaction term in the model). For a variable to be a moderator, it cannot be correlated with the independent variable but exerts its influence on the association between the independent and dependent variable.

Addressing the relationships depicted in Figure 1 and the criterion established above for mediator and moderators, the primary hypotheses tested in this study are: (1) Brain size mediates the influence of age on flight simulator performance. That is, to what extent can age differences in flight simulator performance be explained by brain size? (2) Aviation expertise moderates the impact of brain size on flight simulator performance. That is, does the relationship between brain size and flight simulator performance vary with level of aviation expertise?

Finally, we examined the extent to which education might account for the effect of training and expertise on flight simulator performance.

Materials and Methods

Participants

A total of 51 general aviation pilots (10 women and 41 men) were studied (see Table 1 for demographics, including medication history according to the three aviation expertise levels). Enrollment criteria for magnetic resonance imaging (MRI) study inclusion were age, 50 or older, current FAA medical certificate, and currently flying. Each participant was classified into one of three levels of aviation expertise depending on which FAA proficiency ratings had been previously attained: (1) least expertise: VFR (rated for flying under visual flight rules only); (2) moderate expertise: IFR (also rated for flying under instrument flight rules); and (3) most expertise: CFII or ATP (certified flight instructor of IFR students or rated for flying air-transport planes). Each rating requires progressively more advanced training and more hours of flight experience (for additional details, see Taylor, Kennedy, Noda, & Yesavage, 2007). MRI study participants were selectively recruited from participants of the ongoing longitudinal Stanford/VA Aviation Study so that approximately 50% of MRI participants were APOE $\epsilon 4$ carriers and 50% were $\epsilon 3/3$. Informed consent, approved by Stanford University and VA Palo Alto Health Care System Institutional Review Boards, was obtained from each participant.

Equipment

Pilots “flew” in a Frasca 141 flight simulator (Urbana, IL). The simulator was linked to a computer specialized for graphics (Dell Precision Workstation with a Fedora Linux Operating system, OpenGL C++ software specially customized for a high-end NVIDIA graphics processor) that generated a “through-the-window” visual environment and continuously collected data concerning the aircraft’s position and communication frequencies (see <http://www.stanford.edu/people/yesavage/AIR.html>). 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. A cockpit speaker system was used to present prerecorded audio messages that simulated an air-traffic controller (ATC) speaking to the pilot.

Procedures

Participants had six practice flights during a 1- to 3-week period, after which they had a 3-week break before returning for the test visit. At this visit, the participant flew a 75-min flight in the morning and a 75-min flight in the afternoon. Each flight was followed by a 40- to 60-min battery of cognitive tests. During the flight, pilots heard 16 ATC messages, presented at the rate of 1 message every 3 min, directing the pilot to fly a new heading, a new altitude, dial in a new radio frequency, and in 50% of the legs, dial in a new transponder code. Participants were instructed to read back the ATC messages and then execute them. To further increase workload, pilots were confronted with randomly presented emergency situations: engine malfunctions and/or suddenly approaching air traffic. Pilots were to report engine malfunctions immediately and to avoid air traffic by veering quickly yet safely in the direction diagonal to

the path of the oncoming plane. Pilots flew in severe turbulence throughout the flight, and also encountered a 15-knot crosswind during approach and landing.

Measures

Flight simulator—The scoring system of the flight simulator-computer system produces 23 variables (Yesavage et al., 2002; Yesavage, Taylaor, Mumenthaler, Noda, & O'Hara, 1999) that measure deviations from ideal positions or assigned values (e.g., altitude in feet, heading in degrees, airspeed in knots), or reaction time (in seconds). Because these individual variables have different units of measurement, the raw scores for each variable were converted to Z-scores, using the visit mean and SD of the 141 participants enrolled during 1996–2001 (scores on the morning and afternoon flights were averaged). Flight simulator performance was measured as a single composite Z-score of the four flight tasks: (1) Accuracy of executing ATC-assigned headings, altitudes, radios; (2) Scanning cockpit instruments for engine malfunction (reaction time to report malfunction); (3) Avoiding conflicting air traffic (flying to the diagonally opposite quadrant of the traffic and maximizing distance safely); (4) Executing a visual approach to landing (deviations from ideal course) (Yesavage et al., 1999, 2002).

Speed of processing—Speed of processing was measured using (1) a computerized battery designed for assessment of pilots, CogScreen-AE (Kay, 1995) and (2) two paper-and-pencil tests designed to measure perceptual speed (Pattern Comparison) and reaction time (Digit Copy) (Salthouse, 1996). From CogScreen-AE, we computed a cognitive speed score which was based on Kay's original nine-factor structure (Kay, 1995). Specifically, we computed a composite Z-score (hereafter referred to as cognitive speed) by averaging the three Kay factors that measure timed performance: Visual Scanning and Sequencing (F1), Visual Perceptual and Spatial Processing (F3), and Choice Visual Reaction Time (F5). Note: Our early psychometric work in pilots that were older than Kay's normative sample found that these three factors were intercorrelated along with two other Kay factors (Working Memory-F8 and Numerical Operations-F9) (Taylor, O'Hara, Mumenthaler, & Yesavage, 2000). From the Salthouse tasks, we computed a composite Z-score (hereafter referred to as perceptual-motor speed) by averaging the two Z-transformed Salthouse speed scores (which, for each task, equals the number of items correctly completed during two 30-s trials). These general measures of processing speed were then used as comparative measures in place of flight simulator performance to investigate the effects of age, expertise and whole brain volume.

MR Image acquisition—MRI data were acquired on a 1.5 Tesla (GE Medical Systems, Milwaukee, WI) MRI scanner. Three structural MR sequences were acquired using a standard head coil: (a) a spin-echo, sagittal localizer 2D sequence of 5 mm thick slices; (b) a proton density and T2-weighted spin-echo MRI, TR/TE1/TE2 = 5000/30/80 ms, 51 oblique axial 3-mm slices covering the entire brain and angulated parallel to the long axis of the hippocampal formation ($1.00 \times 1.00 \text{ mm}^2$ in plane resolution); (c) 3D spoiled GRASS MRI of entire brain, TR/TE = 9/2 ms, 15° flip angle, perpendicular to the long axis of the hippocampi ($1.00 \times 1.00 \text{ mm}^2$ in plane resolution, 1.5-mm coronal slices, no skip).

Because the participants of the MRI study were recruited from an ongoing longitudinal study, there was a time lag between a participant's flight simulator visit and MRI scan. There was no correlation of time lag with the outcome variable, flight simulator performance ($p > .1$) or with age ($p > .1$). These time differences by expertise level are provided in Table 1; CFII/ATP had the largest absolute time lag, but it is not significantly larger than the other two expertise groups.

Image processing—All MRI analyses were performed by Dr. Weiner's lab at UCSF. Tissue segmentation was performed on T1-weighted images using Expectation-Maximization

Segmentation (EMS: (Van Leemput, Maes, Vanadermeulen, & Suetens, 1999) to identify gray matter, white matter, and CSF. An atlas-based method was used to identify the lobes of the brain (Collins, 1995; Dawant, Hartmann, Thirion, Maes, Vandermeulen, & Demaerel, 1999; Gee, Reivich, & Bajcsy, 1993; Iosifescu et al., 1997) using the MRI of a cognitively normal healthy 42-year-old man as the reference brain. This reference brain has been manually edited to delineate the hemispheres, major lobes of the brain (right and left frontal, temporal, parietal, and occipital), subcortical structures, brainstem, and cerebellum. An entropy-driven B-Spline Free Form deformation algorithm (Studholme, Cardenas, Maudsley, & Weiner, 2003; Studholme, Novotny, Zubal, & Duncan, 2001) was used to register individual scans to the reference atlas. The use of a cubic B-Spline model of the deformation provides a direct, analytic estimate of the transformation with a continuous derivative for the estimation of local volume change. This transformation was then inverted and applied to the atlas labels to demarcate subject specific regions of interest (ROIs) on each MRI. All automatically parcellated MRIs were carefully visually checked to ensure that the automated markings were accurate. Any ROIs that were incorrectly identified were corrected manually. A final segmented image was then created by combining the atlas-based ROI parcellation and the EMS segmentation. Total intracranial volume (TIV) equaled the sum of all segmented tissue inside the skull (excluding cerebellum and including fluid). TIV correlated strongly with whole brain volume ($r = 0.92$) and was used for normalization of whole brain and lobar volumes. Specifically, whole brain (sum of all gray and white matter) and lobar (parietal, temporal, frontal, and occipital) volumes were adjusted for TIV, based on a regression approach that produced TIV-adjusted residuals. These residuals were then used as predictor variables in the analyses described below.

Statistical Analysis

To evaluate the role of brain size as a mediator of age on flight simulator performance, we first computed coefficients. To assess the role of aviation expertise as a moderator of brain size on flight simulator performance, a multiple regression model was fitted to test the main effects of age, whole brain volume, expertise, and their interactions (SAS PROC GLM, Cary NC). If the whole brain alone or in concert with expertise predicted performance, then additional GLMs were conducted with four TIV-adjusted residuals, frontal, temporal, parietal and occipital volume separately. Age was a continuous variable centered at the median age at time of flight simulator assessment (56.4 years). Expertise also was centered (-1 for VFR, 0 for IFR, 1 for CFII/ATP). Similar analyses were done in which aviation expertise was replaced by years of education centered at the median. (Note: Because Age $\times$ Expertise interactions were not significant in this sample nor in the cohort of 118 participants reported previously (Taylor et al., 2007), this interaction term was dropped from the model). In terms of APOE $\epsilon 4$, there were no significant differences between $\epsilon 4$ carriers and noncarriers with regards to age and education, p values $> .15$. A preliminary GLM revealed no main effect or interactions with APOE $\epsilon 4$ on flight simulator performance. APOE $\epsilon 4$ was, therefore, dropped from the analyses reported below. All calculated p values were two-sided. We also report Spearman's correlation coefficients among age, aviation expertise, education, brain volumes and performance measures.

Results

Demographics

Table 1 summarizes characteristics of the participants at entry, separated by expertise level. Education years greater than 20 years were truncated to 20 years. Higher levels of expertise were associated with more total flight time ($F(2,50) = 22.86$; $p < .001$) and average number of flights per month in past year ($F(2,50) = 4.15$; $p < .05$), as would be expected. No significant differences with respect to expertise level were found in TIV-adjusted whole brain volume, processing speed, or other demographic measures (see Table 1). However, there was a moderate

correlation between education and aviation expertise in this sample ($r = 0.38$; $p < .001$). Of note, this correlation is not present in our larger cohort of pilots ($n = 118$; Taylor et al., 2007).

Brain Size as a Mediator of Age on Flight Simulator Performance

As mentioned above, in order for brain size to be a mediator of age on flight simulator performance, whole brain volume must correlate with age and flight simulator performance. Table 2 illustrates all the relevant correlations; scatter plots in Figure 2 display the relevant relationships. The scatter plot in Figure 2a shows that age is negatively correlated with flight simulator performance ($r = -0.36$; $p < .01$). Age is also negatively correlated with whole brain volume (Figure 2b: $r = -0.41$; $p < .01$). However, whole brain volume does not correlate with flight simulator performance (Figure 2c: $r = 0.22$; $p > .1$). Therefore, the results indicate that whole brain volume may not be mediator of age on flight simulator performance in this sample.

It is possible that, as a consequence of brain aging, pilots might fly less, accumulating fewer nonsimulator hours than before, thereby leading to lower performance in the flight simulator. To test this, a Spearman correlation between non-simulator flight hours in the last year and whole brain volume was performed. This correlation was not significant ($r = -0.021$; $p > .1$).

Aviation Expertise as a Moderator of the Influence of Brain Size on Flight Simulator Performance

In order for aviation expertise to moderate brain size on flight simulator performance, expertise and whole brain volume should not correlate. This correlation was not significant ($r = -0.15$; $p > .1$) indicating that experts did not have larger brains than less expert pilots. (Also, expertise did not diminish the impact of age on whole brain volume (Expertise $\times$ Age interaction: ($F < 1$).

With this condition satisfied, we proceeded to answer the second key question by conducting a multiple regression analysis with expertise, whole brain volume, whole brain volume $\times$ expertise interaction, and age in the model. There were main effects of expertise ($F(1,50) = 7.83$; $p < .01$) and age ($F(1,50) = 8.57$; $p < .01$) on flight simulator performance. These results are similar to previously reported results for all participants in the Stanford/VA Aviation study (Taylor et al., 2007). There was no main effect of whole brain volume ($F < 1$). However, an interaction was observed between expertise and whole brain volume, $F(1,50) = 4.72$; $p < .05$; $ES = 0.30$; see Table 3a). Figure 3 provides a scatter plot of flight simulator performance and whole brain volume in the three expertise groups. The most expert pilots tend to have higher flight simulator scores; and experts with highest scores tend to have larger whole brain volume ($\beta = 0.005$; $SE = 0.001$; $CI = 0.003-0.007$; $p < .001$; $R^2 = 0.83$). This is in contrast to the least expert pilots who tend to have lower flight simulator scores and no positive relationship with whole brain volume ($\beta = -0.006$; $SE = 0.004$; $CI = -0.013-0.002$; $p > .1$; $R^2 = 0.34$). The IFR pilots are intermediate with no apparent relationship with the whole brain volume ($\beta = 0.002$; $S.E = 0.003$; $CI = -0.003-0.007$; $p > .1$; $R^2 = 0.14$). Overall, the slopes of the most expert group (CFII/ATP) and the intermediate (IFR) group did not differ from each other ($p > .1$). The slopes of the intermediate and the least expert groups also did not differ from each other ($p > .1$). However, the slope of the most expert group (CFII/ATP) tends to be different from the least expert (VFR) group ($p = .056$).

We also performed two sets of sensitivity analyses. First, we were concerned that the whole brain volume $\times$ expertise interaction may be driven by an outlier (see Figure 3). This outlier value is due to the score on the flight summary score approach component which was more than three standard deviations below the mean. This score was truncated to be three standard deviations and the analysis reported above was repeated with this truncated value of flight

simulator performance. The brain $\times$ expertise interaction was still significant ($F(1,50) = 4.47$; $p < .05$). Second, as there were no women in the most expert group, we repeated the analysis in men only. The brain $\times$ expertise interaction remained significant ($F(1,40) = 4.91$; $p < .05$).

Table 3a details the significant results from separate GLM models that modeled the four TIV-adjusted residuals for frontal, temporal, parietal, and occipital lobe volume. The robust interaction between expertise and whole brain volume shown above is largely driven by an interaction between expertise and parietal lobe ($F(1,50) = 8.18$; $p < .01$; $ES = .40$; shown in Table 3a). The expertise $\times$ temporal interaction did not reach significance, ($F(1,50) = 3.04$; $p = .09$; not shown in Table 3a), although the effect was in the same direction (positive β_5 parameter estimate). Similar nonsignificant results were observed with frontal and occipital lobes. Finally, no differences for left/right or gray/white matter were found for the parietal lobe. Thus, the total parietal lobe $\times$ expertise level interaction is the most predictive of flight simulator performance, such that aviation expertise moderates the influence of parietal lobe on flight simulator performance.

It is possible that general intelligence and/or reasoning or education may correlate with the kinds of specialized skills that are assessed by flight simulator performance. In fact, there is a moderate correlation between education and aviation expertise ($r = 0.38$; $p < .001$). To address this, we repeated the above analysis with education instead of aviation expertise rating (Table 3b). There was no main effect of education ($F(1,50) = 3.04$; $p > .05$) or whole brain volume ($F(1,50) = 0.18$; $p > .1$) on flight simulator performance. There was a main effect of age ($F(1,50) = 12.07$; $p < .01$). However, an interaction was also observed between education and whole brain volume, $F(1,50) = 5.56$; $p < .05$; $ES = 0.30$). Sensitivity analyses produced the same pattern of results (p 's $> .05$). However, results from the four lobar models revealed no significant lobar $\times$ education interactions. Finally, no differences for left/right or gray/white matter were found.

All three expertise groups were roughly equivalent in age and as expected, total flight time for each pilot group increases with higher levels of expertise. However, it is conceivable that the more experienced pilots logged more total flight time because they learned to fly at a younger age. Therefore, the age when a pilot first attained a private pilot license (referred to as age of licensure) was also analyzed (we thank an anonymous reviewer for this analysis). This age of licensure was significantly correlated with aviation expertise ($r = -0.41$; $p < .01$), but not with years of education ($r = -0.16$; $p > .1$). To address this relationship of age of licensure with aviation expertise, we repeated the above analysis with age of licensure instead of aviation expertise rating. There was a main effect of age of licensure ($\beta = -0.02$; $SE = 0.01$; $p < .001$) and a whole brain volume $\times$ age of licensure interaction ($\beta = -0.0003$; $SE = 0.0001$; $p < .05$).

In light of the overlapping influences of aviation expertise, education and age of licensure, we did a stepwise regression in which all main effects and interactions for brain $\times$ expertise, brain $\times$ education and brain $\times$ age of licensure were entered into the model. The first significant variable was age of licensure ($F(1,50) = 15.36$; $p < .001$; partial $R^2 = 0.24$), followed by age ($F(1,50) = 6.62$; $p < .05$; partial $R^2 = 0.09$), and the brain $\times$ education interaction ($F(1,50) = 5.02$; $p < .05$; partial $R^2 = 0.07$). That age at licensure explains the most variance suggests that specific training at a younger age may help in expertise development because the neural components at time of training are more plastic in nature (Bengtsson, Nagy, Skare, Forsman, Forssberg, & Ullen, 2005). Taken together, education did not predict flight simulator performance; yet, it is likely that education, similar to aviation expertise, moderates the association between whole brain volume and flight simulator performance.

Supplementary Analysis: Processing Speed

Correlations of cognitive speed with all independent variables including age ($r = -0.26$; $p = .07$) and flight simulator performance score ($r = 0.56$; $p < .01$) are provided in Table 2. A GLM was fitted using the processing speed score to compare and contrast the influences of aviation expertise, age, and whole brain volume on cognitive speed with their influences on flight simulator performance. There was no significant main effect of expertise ($\beta = -0.13$; $SE = 0.17$; $p > .1$) and whole brain volume ($\beta = 0.003$; $SE = 0.003$; $p > .1$) on this measure of processing speed per se. Neither age ($F(1,50) = 0.11$; $p = .74$) nor interaction between expertise and whole brain were significant ($F(1,50) = 0.1$; $p > .1$). An analysis using years of education as a predictor variable in place of aviation expertise produced the same pattern of results. When perceptual-motor speed (Salthouse, 1992) was used in a similar GLM, similar results were obtained.

Discussion

We sought to identify the contributions of age, aviation expertise, and brain size on flight simulator performance by systematically following a moderator-mediator statistical approach. We found evidence for moderating but not mediating influences.

Regarding mediation, our results suggest that brain size did not mediate the effect of age on flight simulator performance even though brain size did show age-related decline in this sample. Age-related differences in flight simulator performance reported in this MRI study are consistent with results of cross-sectional analyses of larger Stanford/VA Aviation study cohort—older pilots executed air-traffic controller communications less accurately on average, evaded air-traffic conflicts less adroitly, and approached the runway for landing less precisely (Taylor et al., 2007). This age-related decline in performance is consistent with decline in central sensory functioning (Lindenberger, Scherer, & Baltes, 2001), white matter integrity (Bartzokis, 2004), and brain volume (Raz et al., 2005). Using diffusion tensor imaging (DTI), Sullivan and colleagues (Sullivan et al., 2010) recently surveyed extensive fiber systems throughout the brain. Their study revealed a differential pattern of age-related loss of integrity in white matter and widespread correlations between regional transverse diffusivity and Digit Symbol performance. Evidence from functional neuroimaging (fMRI) studies also suggests that the aging brain exhibits increased prefrontal cortex and posterior parietal cortex task-related activation, leading to theories of compensation or de-differentiation (for a review, see Grady & Craik, 2000). Therefore, in this sample of pilots, we expected age-related decline in brain size, but this decline did not show an influence on flight simulator performance. However, the role of brain aging on flight simulator performance may become clearer when longitudinal outcomes are used or when more sensitive neuroimaging methods are used.

Regarding moderation, we found that the influence of brain size on pilot performance varied with aviation training. That is, aviation expertise may moderate the relationship between brain size and flight simulator performance. Ericsson and Lehman's (1996) view predicts that deliberate practice to master a skill is more important than having a larger brain. Thus, it is not surprising that brain size did not vary across expertise levels. It is also not surprising that greater aviation expertise led to better simulator performance, as skills previously learned within the specific domain of aviation were used. Aviation training and expertise may help these pilots with a larger brain size perform better in the flight simulator than those pilots with smaller brain size. These results fit well with the concept of neurocomputational flexibility which takes into account both the amount of neuronal substrate as well as its plasticity in response to environmental stimuli and/or specialized training to perform a task efficiently.

Additional analyses revealed that the interaction between expertise and brain size was itself largely driven by an interaction between expertise and parietal lobe. Therefore, a larger parietal

lobe (no right or left differences were observed), previously implicated in spatial working memory (Lycke, Specht, Ersland, & Hugdahl, 2008), episodic memory (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008), and retrieval (Cabeza et al., 2008; Wagner, Shannon, Kahn, & Buckner, 2005) in an expert pilot may exert a positive influence on flight simulator performance (see Figure 1). Thus, similar to previous studies, the effect of aviation expertise is constrained to flight simulator performance (Morrow, Menard, Stine-Morrow, Teller, & Bryant, 2001; Morrow, Miller, Ridolfo, Menard, Stine-Morrow, & Magnor, 2005; Taylor et al., 2007). Importantly, these results from the primary analysis show that expertise and brain size interaction remained significant after the main effect of age was taken into account. Therefore, although brain size may be influenced by age, the moderating effect of aviation expertise on brain size still explained a significant amount of variance in flight simulator performance. While aging itself can compromise biological “hardware” (brain volume, working memory capacity, etc), training, and experience in a particular task can help improve the “software” of the cognitive system involved in that task (Charness & Campbell, 1988; Green & Bavelier, 2008). Although there is little or no evidence for any gain from this domain-specific training transferring to performance in general domain tasks, it is possible that transfer can occur across different tasks if certain skill sets are shared (Dahlin, Neely, Larsson, Backman, & Nyberg, 2008; Hertzog et al., 2009). In other words, this interaction could point to successful aging whereby individuals with greater resources (strategies and neurons) execute more efficient cognitive processes. It is also likely that such individuals have higher cognitive reserve—the ability to cope with advancing brain decline by using inherent or acquired cognitive abilities (Stern, 2006).

Results also indicate that education moderated the effect of brain size on flight simulator performance. We surmise that education may be partially mediating aviation expertise while not influencing flight simulator performance directly. This is because some skill sets required in aviation training, (e.g., the motivation, strategies of test-taking), may be shared with the same skills involved in educational success. This idea is demonstrated by the aforementioned modest correlation between aviation expertise and education that was observed in this sample. It should be noted that this correlation was not significant in the large cohort of pilots involved in the ongoing longitudinal study. Moreover, our findings regarding education need to be replicated in a larger sample and compared with measures of global cognitive function and/or proxy measures of IQ (Spinks, McKirgan, Arndt, Caspers, Yucuis, & Pfalzgraf, 2009).

There are several other limitations to this study. First, as mentioned above we used years of education when the gold standard measure of IQ would be ideal. Second, the relatively small sample size makes it difficult to separate the effects of education and aviation expertise. Third, the sample consists mostly of men. Even though all the analyses that yielded significant results were repeated in a men only sample, it would be better to increase the representation of women in the sample. Fourth, we would also like to include younger pilots to obtain a broader age distribution which will increase our ability to characterize the neural efficiency of expertise. Finally, cross-sectional volumetric analysis measures the normal variation in brain morphology as well as age-related changes that have taken place up to the time of the MRI scan. Age-related atrophy is ideally measured longitudinally. Advanced neuroimaging techniques such as fMRI and DTI, that measure brain function and/or integrity, can provide additional insights into learning about the differential contributions of age, expertise and brain structure and function. Despite these limitations, this preliminary study contributes to the existing literature of the influence of protective factors on cognitive aging.

Overall, the results point to the benefits of combining expertise, education, age, and brain size to understand the protective and deleterious influences on the aging brain. Although in this study, expert knowledge and education did not show evidence of reducing the age-related decline in brain size, or confer a larger brain, certain interventions across the lifespan may

enrich the biological substrate of the brain. Brain size is positively correlated with intellectual ability (MacLullich, Ferguson, Deary, Seckl, Starr, & Wardlaw, 2002; Mori et al., 1997). In addition, brain size is also under the influence of environment stimulation, neuroplasticity, and the deleterious influences of aging (Stern, 2006). In fact, brain size measure not only provides a tangible way to grasp neuronal density, but because it is influenced by experience and age, it also can speak to neurocomputational flexibility. There are other robust ways of measuring neuronal density or increase in synaptic plasticity that are evident in animal literature (Artola et al., 2006). Volumetric MRI studies in humans do show regional influences of motor-skill training (Driemeyer, Boyke, Gaser, Buchel, & May, 2008) and physical exercise (Colcombe et al., 2006). Similarly, functional imaging studies also show differences in brain functioning related to various measures of education (Sole-Padulles et al., 2009; Springer, McIntosh, Winocur, & Grady, 2005) and changes as a result of cognitive training (Olesen, Westerberg, & Klingberg, 2004; Valenzuela et al., 2003).

The results from the present study strongly suggest that both expertise and/or education may influence performance of a domain-specific task by interacting with the size of an aging brain. Therefore, it is critical to include various measures of expertise and/or education when investigating age-related changes in cognitive and brain function. Integrative approaches that combine real-world cognitive measures with neuroimaging techniques can provide a detailed assessment of how protective factors can enrich everyday cognition in the aging population.

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Fig. 1.

A theoretical construct depicting the influence of expert training and skill (aviation expertise) along with age and total intracranial volume (TIV) -adjusted whole brain volume on flight simulator performance in pilots.

Fig. 2.

Scatter plots of (a) flight summary score with age, (b) whole brain volume with age, and (c) flight summary score with whole brain volume. Whole brain volume is total intracranial volume (TIV) -adjusted. All points on the graph are divided into the three aviation expertise levels (see legend). Correlations are provided on each graph. ¹Note, the distribution of whole brain size is concentrated toward larger brain volume; however, there is no correlation between brain size and expertise. VFR = rated for flying under visual flight rules only; IFR = rated for flying under instrument flight rules; CFII = certified flight instructor; ATP = rated for flying air-transport planes.

Fig. 3.

Relationship between flight simulator performance and whole brain volume: Scatter plot according to aviation expertise rating. Trend lines are shown for each aviation rating group as per the parameters estimated by the general linear model: Predicted flight simulator summary Z-score = $2.022 + 0.001 * (\text{whole brain volume}) + 0.260 * (\text{rating}) + 0.004 * (\text{whole brain volume}) * (\text{rating}) - 0.034 * (\text{average age for each rating group})$ where Rating of -1, 0, and 1 represents VFR, IFR, and CFII/ATP, respectively. Whole brain volume is residualized on TIV. VFR = rated for flying under visual flight rules only; IFR = rated for flying under instrument flight rules; CFII = certified flight instructor; ATP = rated for flying air-transport planes.

Table 1Demographic characteristics (mean $\pm$ SD) of the 51 participants by aviation expertise¹

	VFR <i>n</i> = 18	IFR <i>n</i> = 22	CFII/ATP <i>n</i> = 11
Age, y, mean $\pm$ SD	56.7 $\pm$ 7.8 (age-range = 45.5-68.7)	58.9 $\pm$ 4.8 (age-range = 48.6-68.1)	53.4 $\pm$ 5.5 (age-range = 46-64.7)
Age of licensure, y, mean $\pm$ SD ²	38.3 $\pm$ 12.9	34.4 $\pm$ 12.7	24.0 $\pm$ 4.1
Education, y, mean $\pm$ SD	16.2 $\pm$ 7.9 [*]	17.5 $\pm$ 4.8 [*]	18.1 $\pm$ 5.5 [*]
No. white, non-Hispanic	16	22	9
No. men	13	17	11
No. hypertension medication use ever	3	5	3
No. statin use ever	3	6	2
APOE ϵ 4 carriers	10	9	5
No. Type II diabetes	0	1	0
No. LOC/concussion ³	2	3	0
No. family history of dementia (yes/no/not sure)	4/13/1	6/13/3	1/10/0
No. employment status Full-time/part-time/self Employed/unemployed/retired	11/2/1/2/2	6/1/4/2/9	8/0/2/1/0
No. FAA medical Class I, II, or III. ⁴	0/3/15	0/6/16	6/4/1
Total flight time, h, median $\pm$ SD ⁵	598 $\pm$ 429 ^{**}	1493 $\pm$ 973 ^{**}	3219 $\pm$ 1622 ^{**}
Nonsimulator flight hours in past year, h, mean $\pm$ SD ⁶	91.83 $\pm$ 162 ^{*a}	71.90 $\pm$ 76.46 ^{**b}	289.55 $\pm$ 322.48
No. medical waivers ⁷	0	2	0
Time lag, y, mean $\pm$ SD ⁸	4.07 $\pm$ 3.2	4.18 $\pm$ 2.99	4.99 $\pm$ 2.71
Whole brain volume (cc) ⁹	1080.88 $\pm$ 39.10	1063.41 $\pm$ 38.47	1066.50 $\pm$ 56.96
Perceptual-motor speed (z-score) ¹⁰	0.28 $\pm$ 0.80	-0.09 $\pm$ 0.93	0.05 $\pm$ 0.69
Cognitive speed (z-score) ¹¹	0.039 $\pm$ 0.48	-0.25 $\pm$ 0.63	0.0094 $\pm$ 0.27
Flight simulator performance (z-score)	-0.17 $\pm$ 0.69	-0.01 $\pm$ 0.46	0.39 $\pm$ 0.34

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

¹ VFR: rated for flying under visual conditions, which restricts a pilot to flying only in good visibility conditions, is the rating given to pilots when they first obtain a license. IFR: instrument rated, which allows a pilot to fly in poorer visibility conditions using navigational instruments. CFII: certified flight instructor of pilots in training for IFR. ATP: certified to fly air-transport planes. Major airline captains have the ATP rating.

² Age of licensure: the age when a pilot first attained a private pilot license.

³ Loss of Consciousness (LOC) or concussions were caused by minor accidents in childhood. None of these lasted for more than 15 minutes.

⁴ Pilots are required to pass periodic medical examinations to fly. Class I and II medical certificates have higher standards for distant and near vision than Class III; a Class I certificate requires an ECG at age 35 and annually after age 40, but Class II and III do not routinely require them. A Class I medical certificate indicates that the pilot has passed a medical examination within the past 6 months; a Class II medical certificate indicates passing the examination within the past 1 year; a Class III medical certificate indicates passage within the past 2 years. Due to this medical monitoring, pilots are typically in good health.

⁵ CFII/ATP group had more total flight hours than the IFR group, and the IFR group had more total flight hours than the VFR group (PROC GLM; $p < 0.01$). The CFII/ATP group had more recent flight hours than the VFR group ($p < 0.01$).

⁶ Non-simulator flight hours in the past year. CFII/ATP was used as a reference to determine whether these hours were different across the three groups of aviation expertise. ^alog hours are significantly different between VFR and CFII/ATP ($p < .05$). ^blog hours are significantly different between IFR and CFII/ATP ($p < .001$).

⁷ A few (2/51) had a medical waiver which allows a pilot to have a valid Federal Aviation Administration (FAA) medical certification despite having a disqualifying medical condition.

⁸ Time difference in years between first flight simulator performance and first MRI scan.

⁹ Whole brain volume is the sum of gray and white matter, residualized on Total Intracranial Volume (TIV). Values represent the residual plus average of non-residualized whole brain volume for clarity.

¹⁰ Composite Z-score of Pattern Comparison and Digit Copying (Salthouse, 1992), were used to measure speed of processing.

¹¹ An overall speed-of-processing z-composite score was calculated by averaging the three Kay factors that measure timed performance: Visual Scanning and Sequencing (F1), Visual Perceptual and Spatial Processing (F3) and Choice Visual Reaction Time (F5: Kay, 1995).

Table 2

Spearman's correlation among study variables, including lobar volume, flight simulator performance composite and individual scores, age, years of education, cognitive speed, and perceptual-motor speed scores. Spearman correlation coefficients of an absolute magnitude .20 were significant ($p < .05$).

	Cognitive speed of processing	Perceptual-motor speed	Flight performance	Aviation expertise	Age	Years of education	Non-sim hours past year	Whole brain volume	Parietal lobe,= volume	Frontal lobe volume	Temporal lobe volume	Communication	Approach	Avoidance	Emergency	TIV
Cognitive speed ¹		0.62	0.56	-0.11	-0.26	-0.05	0.09	0.19	0.03	0.14	0.10	0.47	0.43	0.36	0.37	0.10
Perceptual-motor speed ²	0.62		0.28	-0.13	-0.10	0.07	-0.10	0.20	0.12	0.13	0.07	0.23	0.05	0.20	0.32	0.09
Flight performance ³	0.56	0.28		0.32	-0.36	0.08	0.18	0.22	0.09	0.17	0.16	0.81	0.66	0.59	0.74	0.19
Aviation expertise ⁴	-0.11	-0.13	0.32		-0.10	0.38	0.36	-0.15	-0.22	-0.07	-0.03	0.25	0.26	0.35	0.17	0.21
Age ⁵	-0.26	-0.10	-0.36	-0.10		0.00	-0.06	-0.41	-0.05	-0.36	-0.25	-0.35	-0.24	-0.12	-0.28	0.04
Years of education ⁶	-0.05	0.07	0.08	0.38	0.00		0.02	-0.08	-0.33	-0.02	-0.01	0.12	0.04	0.07	0.02	-0.05
Non-sim hours past year ⁷	0.09	-0.10	0.18	0.36	-0.06	0.02		-0.14	-0.06	-0.14	-0.06	0.12	0.17	0.10	0.20	0.39
Whole brain volume ⁸	0.19	0.20	0.22	-0.15	-0.41	-0.08	-0.14		0.51	0.68	0.49	0.24	0.06	0.12	0.14	-0.03
Parietal Lobe volume	0.03	0.12	0.09	-0.22	-0.05	-0.33	-0.06	0.51		0.06	0.35	0.16	-0.13	0.10	0.09	-0.05
Frontal lobe volume	0.14	0.13	0.17	-0.07	-0.36	-0.02	-0.14	0.68	0.06		0.16	0.20	0.07	-0.09	0.08	-0.16
Temporal lobe volume	0.10	0.07	0.16	-0.03	-0.25	-0.01	-0.06	0.49	0.35	0.16		0.24	-0.02	0.24	0.07	0.07
Communication ⁹	0.47	0.23	0.81	0.25	-0.35	0.12	0.12	0.24	0.16	0.20	0.24		0.54	0.31	0.42	0.13
Approach ¹⁰	0.43	0.05	0.66	0.26	-0.24	0.04	0.17	0.06	-0.13	0.07	-0.02	0.54		0.35	0.20	0.17
Avoidance ¹¹	0.36	0.20	0.59	0.35	-0.12	0.07	0.10	0.12	0.10	-0.09	0.24	0.31	0.35		0.30	0.20
Emergency ¹²	0.37	0.32	0.74	0.17	-0.28	0.02	0.20	0.14	0.09	0.08	0.07	0.42	0.20	0.30		0.13
TIV ¹³	0.10	0.09	0.19	0.21	0.04	-0.05	0.39	-0.03	-0.05	-0.16	0.07	0.13	0.17	0.20	0.13	

¹ Cognitive Speed: a composite z-score created by following methods described in detail in Taylor et al., 2000.

² A composite z-score of Pattern Comparison and Digit Copying (Salthouse, 1992) were used to measure speed of processing.

³ Flight Performance: a composite z-score of the four flight tasks; (see Taylor 2007 for details).

⁴ Aviation Expertise: measured by FAA proficiency ratings which provide an ordinal measure of lifetime aviation training and experience (see Table 1).

⁵ Age: measured at the time of the time of flight simulator performance.

⁶ Years of Education: Years of education are truncated to 20 years.

⁷ Non-sim hours past year: number of hours accumulated flying (non-simulator) in the past year.

⁸ Whole brain volume: To adjust for head size, residualized brain volumes, whole brain, parietal, frontal and temporal) adjusted for TIV (in cc units) were used.

⁹ Communication: Executing ATC-assigned headings, altitudes, radios.

¹⁰ Approach: Executing a visual approach to landing.

¹¹ Avoidance: Avoiding conflicting air traffic.

¹² Emergency: Scanning cockpit instruments for engine problems.

¹³ TIV: Total intracranial volume (cc).

Table 3

Table 3a. Relationships of whole brain volume, age, and aviation expertise with flight simulator summary score: Summary of multiple regression model result (parameter estimates $\pm$ SE and overall R^2).[†] Also shown are the parameter estimates for the one lobe that showed a significant interaction with expertise.

Flight summary score ¹	Intercept (β_0)	Brain ² (β_1)	Age (β_2)	Expertise ³ (β_4)	Expertise $\times$ Brain (β_5)	Overall $F(1,44)$	Overall R^2
Whole Brain	0.083 $\pm$ 0.071	0.001 $\pm$ 0.002	– 0.034** $\pm$ 0.012	0.260** $\pm$ 0.093	0.004* $\pm$ 0.002	5.58**	0.33
		Parietal lobe					
	0.106 $\pm$ 0.067	0.006 $\pm$ 0.005	–0.036** $\pm$ 0.011	0.266** $\pm$ 0.090	0.015** $\pm$ 0.005	6.93**	0.38

Table 3b. Relationships of whole brain volume, age, and years of education with flight simulator summary score: Summary of multiple regression model result (parameter estimates $\pm$ SE and overall R^2).[†]

Flight summary score ¹	Intercept (β_0)	Whole brain (β_1)	Age (β_2)	Years of education ⁴ (β_4)	Education $\times$ Brain (β_5)	Overall $F(1,44)$	Overall R^2
	0.035 $\pm$ 0.070	–0.001 $\pm$ 0.002	–0.039** $\pm$ 0.012	0.055 $\pm$ 0.033	0.001* $\pm$ 0.001	3.61*	0.24

Table 3c. Supplementary analysis: Relationships of whole brain volume, age, and aviation expertise with cognitive speed (Cogscreen-AE). Summary of multiple regression model result (parameter estimates $\pm$ SE and overall R^2).[†]

Cognitive speed ⁵	Intercept (β_0)	Whole brain (β_1)	Age (β_2)	Expertise (β_4)	Expertise $\times$ Brain (β_5)	Overall $F(1,44)$	Overall R^2
	–0.083 $\pm$ 0.080	0.001 $\pm$ 0.002	–0.02 $\pm$ 0.013	–0.061 $\pm$ 0.105	0.001 $\pm$ 0.002	0.86	0.07

* $p < .05$;

** $p < .01$.

¹ Overall flight simulator performance is indexed by a “flight summary score,” which is a composite Z-score of the flight tasks (see Taylor 2007 for details). Note, none of the components of the flight summary score (approach, communications, avoidance, and emergency) showed any significant results when they were each entered as the outcome variable in a GLM model (correlations are provided in Table 2).

² To adjust for head size, residualized brain volumes adjusted for TIV (in cc units) were used.

³ Expertise is measured by FAA proficiency ratings, which provide an ordinal measure of lifetime aviation training and experience.

⁴ Years of education was truncated to 20 if participants reported more than 20 years.

⁵ Cognitive speed is a composite Z-score of Cogscreen-AE measure (see Taylor et al., 2000 for details).

[†]To address the uneven distribution of gender across expertise levels (i.e., no women in the CFII/ATP group), the same analysis was done in men only. The Whole Brain $\times$ Expertise interaction remained significant, $F(1, 40) = 4.91, p < .05, ES = 0.30$) as did the Parietal Lobe $\times$ Expertise interaction.