Published in final edited form as:

Cogn Neurosci. 2011 January 1; 2(1): 1–10. doi:10.1080/17588928.2010.512974.

Age-Dependent Relationships between Prefrontal Cortex Activation and Processing Efficiency

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Abstract

fMRI was used in the present study to examine the neural basis for age-related differences in processing efficiency, particularly targeting prefrontal cortex (PFC). During scanning, older and younger participants completed a processing efficiency task in which they determined on each trial whether a symbol-number pair appeared in a simultaneously presented array of nine symbol-number pairs. Estimates of task-related BOLD signal-change were obtained for each participant. These estimates were then correlated with the participants' performance on the task. For younger participants, BOLD signal-change within PFC decreased with better performance, but for older participants, BOLD signal-change within PFC increased with better performance. The results support the hypothesis that the availability and use of PFC resources mediates age-related changes in processing efficiency.

The present study examined whether age-related declines in processing efficiency depend on prefrontal cortex (PFC) function. Behavioral studies have shown that age-related processing efficiency declines mediate broad declines in cognitive abilities observed with advancing age (see Salthouse, 1996). Furthermore, neuroimaging studies suggest that age-related declines in processing efficiency might depend on PFC function (e.g., Rypma & D'Esposito, 2000; Rypma et al., 2006).

Generally, processing efficiency has been defined as the time needed to execute relatively simple cognitive operations (see Salthouse, 1996). It has been operationalized as the time taken to correctly make perceptual/cognitive decisions (e.g., Buckhalt, 1991; Earles & Salthouse, 1995; Salthouse, 1992), as the number of correct perceptual/cognitive decisions made within a limited amount of time (e.g., Ekstrom, French, & Harman, 1979; Wechsler, 1997), and as a latent variable emerging when timed domain specific tests are used (e.g., Carroll & Maxwell, 1979). Processing efficiency tasks are designed to be simple enough to minimize the influence of semantic knowledge, memory, and strategy on performance, but they are designed to be complex enough to assess more than mere variability in sensorimotor function (see Carroll & Maxwell, 1979; Jensen, 1993; Vernon, 1983).

Age-related declines have been documented on a variety of processing efficiency tasks (e.g., Finkel, Reynolds, McArdle, & Pedersen, 2005; Park & Hedden, 2001; Salthouse, 1992; Wielgos & Cunningham, 1999), and statistical control of individual differences in

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Parts of this research were presented at the 16th Annual Meeting of the Cognitive Neuroscience Society, San Francisco, CA, and at the 38th Annual Meeting of the Society for Neuroscience, Washington, DC.

processing efficiency has been shown to attenuate age-related declines in a range of higher-order cognitive abilities (see Salthouse, 1996; but see McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010). These attenuation effects suggest that processing efficiency decline is a general mechanism accounting for broad age-related cognitive declines. Furthermore, one model proposes that processing efficiency declines are due to cascading failures, originating in lower-order processes, leading to failures in higher-order processes (Salthouse, 1996).

fMRI research on aging, individual differences in cognitive abilities, and PFC function suggest that processing efficiency might be differentially related to PFC function for older and younger adults (Rypma & D'Esposito, 2000; Spreng, Wojtowicz, & Grady, 2010). Faster retrieval speed on WM tasks, for example, has been associated with lower PFC activation for younger adults but higher PFC activation for older adults (e.g., Rypma & D'Esposito, 2000; Rypma et al., 2005). WM and processing efficiency, however, have both unique and shared influences on age-related cognitive decline (McCabe & Hartman, 2008; McCabe et al., 2010; Salthouse, 1991; Salthouse & Ferrer-Caja, 2003), and age differences in relationships between task-related PFC activation and memory measures other than retrieval speed have been observed (e.g., episodic memory retrieval, Duverne, Motamedinia, & Rugg, 2009; WM span, Schneider-Garces et al., 2009). Thus, it is not clear whether previously reported age differences in the relationship between PFC activation and the measures of retrieval speed were functions of WM, *per se*, or processing efficiency.

The relationship between processing efficiency and PFC function previously has been examined more directly in younger adults (Rypma et al., 2006). While fMRI data were collected, participants completed the Digit Symbol Verification Task (DSVT), a computerized measure of processing efficiency adapted from Digit-Symbol Coding (Wechsler, 1997). Worse performing young adults showed greater signal-change within dorsal PFC than their better performing counterparts, consistent with the worse performing younger adults more strongly recruiting PFC resources to modulate underperforming lower-order processes. These effects, however, have not been examined in older adults.

The present fMRI study sought evidence for the differential relationship between PFC recruitment and processing efficiency for older and younger adults by examining the relationship between age, DSVT performance, and brain activation. If processing efficiency for older adults depends on PFC resource availability to modulate sub-optimally functioning lower-order operations, then better performing older adults should show evidence of greater PFC resource use compared to worse performing older adults and better performing younger adults.

Method

Participants

Nineteen older adults (age $M=58$; range=50 to 69; 14 females) and 19 younger adults (age $M=23$; range=18 to 31; 9 females) participated in the study. They were recruited through advertisements posted on the campuses of the University of Texas at Dallas, the University of Texas Southwestern Medical Center, and the surrounding communities. Older adults were prescreened for participation in the study using the Telephone Interview for Cognitive Status (de Jager, Budge, & Clarke, 2003), and none of those selected scored below the criterion of 22 ($M=27$). All participants were prescreened for MRI contra-indicators and for medical, neurological, and psychiatric illness. The experiment was approved by the Institutional Review Boards at the University of Texas at Dallas and University of Texas Southwestern Medical Center, and the experiment was conducted according to the principles expressed in the Declaration of Helsinki. Written informed consent was obtained from each participant prior to testing.

Procedure

Participants completed the DSVT (Rypma et al., 2006) modeled after the Digit-Symbol Coding task from the WAIS-III-R (Wechsler, 1997) and previously used computerized Digit-Symbol processing efficiency tasks (e.g., Earles & Salthouse, 1995; Salthouse, 1992). DSVT performance correlates with Digit-Symbol Coding performance, as previously reported (Rypma et al., 2006) and found in a separate sample of younger participants ($n = 34$, 20 females; age $M = 24$; DSVT RT $M = 1690$, $SD = 278$, proportion correct $M = .94$, $SD = .03$; Digit Symbol Coding number correct $M = 90.59$, $SD = 10.43$; DSVT RT $r = -.48$, $p < .05$, and DSVT proportion correct $r = .35$, $p < .05$). Furthermore, previously used computerized measures similar to the DSVT also have been shown to correlate with other measures of processing efficiency (ranging from $.35 < |r| < .90$) and age (ranging from $.35 < |r| < .60$) and to significantly control for age-related variance in a host of cognitive ability measures (see Salthouse, 1996).

On each trial, a table containing nine digit-symbol pairs and a single digit-symbol probe (Figure 1) appeared simultaneously for 3.5 s. Participants had until the end of the trial display time to indicate whether the probe-pair matched a symbol-number pair in the key or not. RT was measured from the trial onset to the time of the response (right thumb button-press yes and left for no).

There were 156 trials over three scanning runs (approximately 52 trials per run). On half the trials, the probe-pair matched one of the digit-symbol pairs in the table, and on the other half, the probe-pair did not. Trials for each run were randomly intermixed (jittered) with twenty-three 4 s rest periods. Digit-symbol pairings in the table varied randomly across trials to discourage memory-based strategies.

Stimuli were projected onto a screen at the rear of the bore of the scanner and were viewed by the participants via an angled mirror positioned above the receiving coil, with the midpoint of the mirror approximately 12 cm from a participant's eye. Key and probe symbols and digits were black appearing within white squares, approximately $.4 \times .4$ cm measured at the mirror ($\approx 1.95^\circ$ visual angle), all on a black background. The full key measured approximately $4 \times .85$ cm ($\approx 18.6^\circ \times 4.05^\circ$ visual angle), and the top of the key to the bottom of the probe measured approximately 1.75 cm ($\approx 8.3^\circ$ visual angle).

Image Acquisition

High-resolution anatomical images (MPRAGE; 1 mm isovoxel; sagittal; TE = 3.7 ms; flip angle = 12°) and functional images using (EPI; voxel = $3.5 \times 3.5 \times 4$ mm; 36 slices/volume; 150 volumes/run; TR = 2000 ms, TE = 30 ms; flip angle = 70° ; matrix = 64×64 ; axial; inferior to superior interleaved) were collected on a Philips Achieva 3T scanner equipped with an 8-element, SENSE, receive-only head coil. Six “dummy” scans occurred at the beginning of each functional run to remove T1 saturation effects.

Image Analysis

The fMRI data were analyzed using AFNI software (Cox, 1996). The data for individual participants were corrected for slice-timing offset and motion, and then spatially filtered with a Gaussian kernel (FWHM = 8 mm). For each run, the data for each voxel were then scaled so that the deconvolution parameter estimates would be expressed in terms of percent signal-change (i.e., $100 * y_t/M_y$, t = time point), and the preprocessed BOLD time-series per voxel were then deconvolved using modified linear regression, with the regressor constructed by convolving a hemodynamic response model (a gamma-variate function; Cohen [1997] parameters $b = 8.6$, $c = 0.547$; max amplitude = 1.0) with a task-reference function for correct responses and with nuisance regressors for linear, quadratic, and cubic

trends for each run and for the motion correction parameters included in the regression model. The percent signal-change matrix for each participant was spatially normalized to Talairach space via a 12-parameter affine transformation (Talairach & Tournoux, 1988; resampled to a 2 mm isovoxel resolution), and the spatially normalized percent signal-change estimates were used in a random effects, hierarchical, regression analysis to identify regions where the relationship between performance and activation significantly differed between the groups.

For the regression analyses, DSVT performance was calculated as the z-standardized proportion correct minus z-standardized RT, with the standardized values computed per age-group, and the difference was divided by two. Using this calculation, higher positive values indicate better performance. Although, RT often has been used as the primary index of processing efficiency, accuracy also has been used when participants were to respond within a limited amount of time (e.g., Digit-Symbol Substitution, Wechsler, 1997). The limited response period (3.5 s per trial) in the present task, therefore, created a situation where both speed and accuracy had potential diagnostic relevance.

The primary question of interest was whether PFC activation would be differentially related to performance (i.e., processing efficiency) for younger and older adults. These interaction effects were evaluated using hierarchical linear regression comparing variance reduction by a full regression model, where Percent Signal-Change = $B[\text{DSVT-Performance}] + B[\text{Age-Group}] + B[\text{DSVT-Performance} \times \text{Age-Group}] + \text{error}_{\text{full}}$, was compared to variance reduction by a reduced regression model, where Percent Signal-Change = $B[\text{DSVT-Performance}] + B[\text{Age-Group}] + \text{error}_{\text{reduced}}$. Dividing $\text{error}_{\text{reduced}}$ by $\text{error}_{\text{full}}$ allows for the assessment of variance reduction due to the inclusion of the interaction term (i.e., the identification of voxels in which the Performance $\times$ Age-Group interaction is significant). Additionally, main effects of performance and age-group also were evaluated to identify voxels where percent signal-change varied linearly with performance regardless of age-group and where percent signal-change means for the younger and older adults significantly differed from each other. To control for family-wise Type I errors, the results were cluster-thresholded based on Monte-Carlo simulations (AlphaSim software; Ward, 2000) so that surviving clusters were significant with a family-wise $\alpha = .05$ and a voxel-level $\alpha = .005$. Clusters of 1160 μL (at 2 mm isovoxel, 145 voxels) were significant with family-wise $\alpha = .05$, based on the simulations (1000 iterations for a dataset having 168,505 voxels [2 mm isovoxel], smoothness = 8 mm FWHM, cluster = pairs of voxels having a connectivity radius < 3.47 mm, thus having connecting faces, edges, or corners at the resampled voxel size).

Results

Behavioral Results

RTs for incorrect responses and outliers (RTs > |2.5| SDs from a participant's mean) were discarded. The older adults were significantly slower and less accurate ($RT M=1739$ ms, $SD=227$ ms; *Proportion Correct* $M=.949$; $SD=0.021$) than the younger adults ($RT M=1355$ ms, $SD=223$ ms; *Proportion Correct* $M=.959$; $SD=0.008$), $RT t(36) = 5.27$, $p < .001$ (M difference=384, $SE=73$), and *Proportion Correct* $t(36) = 2.06$, $p < .05$ (M difference=.011, $SE=.005$).

RT and accuracy were negatively correlated for both groups, for older adults $r = -.53$, $p < .05$, and for younger adults $r = -.26$, $p > .05$. Thus, in general, slower participants were also less accurate, suggesting that speed-accuracy trade-off was not an issue at the group level, and visual inspection of a scatterplot of the normalized RT data as a function of normalized accuracy did not reveal evidence of speed-accuracy trade-off for any of the participants.

Furthermore, the correlations supported the use of the combined speed and accuracy measures for the regression analysis.

fMRI Results

Interaction Effects—Hierarchical regression revealed five clusters of voxels where the correlations between DSVT performance and percent signal-change significantly differed between the older and younger adults (Figure 2). Significant differences in correlations were found bilaterally in left and right middle frontal gyri with peak correlations in right and left BA 9/10 and right BA6 (Table 1A). For these clusters, better performance among the younger adults was associated with lower BOLD signal-change (Figure 3), but better performance among the older adults was associated with higher BOLD signal-change (Figure 3). Scaling the BOLD signal-change amplitude estimates for possible vascular contributions, based on resting-state EPI signal-change variability (Kannurpatti, Motes, Rypma, & Biswal, 2010, *in press*), did not affect these interaction patterns. Furthermore, these interaction effects were present for both RT and accuracy (Figure 2B & 2C). Faster RT and greater accuracy for younger adults was associated with lower BOLD signal-change within both left (for percent signal-change from Figure 3, RT $r = .47$, $p < .05$, and accuracy $r = -.46$, $p < .05$) and right PFC (for percent signal-change from Figure 3, RT $r = .55$, $p < .05$, and accuracy $r = -.62$, $p < .05$), but faster RT and greater accuracy for older adults was associated with greater BOLD signal-change within both left (for percent signal-change from Figure 3, RT $r = -.55$, $p < .05$, and accuracy $r = .83$, $p < .05$) and right PFC (for percent signal-change from Figure 3, RT $r = -.49$, $p < .05$, and accuracy $r = .79$, $p < .05$).

Significant correlations also were found with peak coefficients in left temporal pole (peak in BA 38) and right cerebellum (Table 1A). For these clusters, better performance among younger adults was associated with lower BOLD signal-change; whereas better performance among older adults was associated with higher BOLD signal-change.

Main Effects—Regression of percent signal-change on performance alone revealed two significant clusters of cortical voxels (Figure 4A, Table 1B), within parts of left middle frontal gyrus (peak in BA 46) and parts of middle occipital gyrus (peak in BA 19). For both clusters, better performance was associated with higher signal-change. Significant correlations also were found bilaterally within the cerebellum (Table 1B), with better performance also associated with higher signal-change. Thus, better performing older and younger adults relied on these resources more than their worse performing counterparts, providing evidence of functional dissociations between age-independent and age-dependent resource use related to performance.

Regression of percent signal-change on age-group alone revealed significant clusters of voxels where percent signal-change differed between the groups (Figure 4B). Significant differences were found bilaterally in motor cortex, with older adults (left $M = 0.17\%$, $SEM = 0.022$; right $M = 0.21\%$, $SEM = 0.033$) showing greater signal-change than younger adults (left $M = 0.01\%$, $SEM = 0.018$; right $M = 0.05\%$, $SEM = 0.028$). Significant clusters also were found within visual cortex and within right parahippocampus, with younger adults (visual: $M = 0.74\%$, $SEM = 0.064$; parahippocampus: $M = 0.24\%$, $SEM = 0.034$) showing greater signal-change than older adults (visual: $M = 0.32\%$, $SEM = 0.048$; parahippocampus: $M = 0.06\%$, $SEM = 0.018$). Thus, these data provided evidence of functional dissociations between performance-independent and performance-dependent age-related changes in resource use.

Discussion

The results provided evidence that PFC function mediates age-related differences in processing efficiency. For younger adults, better performance on the DSVT was associated with lower PFC BOLD signal-change, but for older adults, better performance was associated with higher PFC BOLD signal-change. Thus, these data suggest that better processing efficiency for younger adults was associated with the less use of PFC-mediated resources, but better processing efficiency for older adults was associated with the more use of PFC-mediated resources.

The separate analyses of RT and accuracy revealed interaction effects for both measures, but slightly stronger effects for accuracy. Although accuracy was relatively high for both groups, slower performers might have guessed more often due to reaching an internal response deadline before accumulating enough information to meet response criteria (Ratcliff & Rouder, 1998), especially given the external 3.5 s response deadline for the present task. For both older and younger adults, errors tend to increase with RT when emphasizing accuracy over speed (Ratcliff, Thapar, & McKoon, 2001), and in the present study, participants were told that both accuracy and speed were equally important. Additionally, at least for older adults as a group, choice RT studies suggest that they do set higher response criteria (Ratcliff, Thapar, & McKoon, 2001, 2006; Smith & Brewer, 1995; Hertzog, Vernon & Rypma, 1993) or are simply slower at accumulating or integrating enough information to meet response criteria (Rousselet et al., 2009; Salthouse & Somberg, 1982). The slowing of the accumulation or integration of information and subsequent increased guessing with longer processing times might explain individual variability within older and younger groups and might lead to correlations between RT and accuracy, as in the present processing efficiency task.

Age-differential activation-performance relationships similar to those found in PFC also were found in regions of the left temporal pole, left basal ganglia, and right cerebellum. The age-differential PFC activation-performance relationship in this processing efficiency task replicates findings from earlier studies using more complex WM tasks (e.g., Rypma & D'Esposito, 1999; Rypma, Eldreth, & Rebbecki, 2007) and suggests a central role for PFC in age-related performance differences. The correlations in other brain regions, however, suggest that PFC is part of a network of regions that might mediate age-related differences in processing efficiency.

The age-group differences found in the relationship between PFC activation and processing efficiency demonstrate the importance of evaluating such relationships in studies examining the neural mechanisms mediating age-related cognitive decline. fMRI studies investigating the neural mechanisms mediating age-related cognitive declines often examine age-related differences in mean or median task-related BOLD signal-change. These studies have provided characterizations of brain mechanisms mediating cognitive aging and have led to hypotheses about age-related functional loss (e.g., Rypma, Prabhakaran, Desmond, & Gabrieli, 2001; Stebbins et al., 2002; Logan et al., 2002) and the engagement of compensatory processes (see Cabeza, 2002; Grady, 2008; Park & Reuter-Lorenz, 2009; Stern, 2002). Less activation of older adults compared to younger adults has been interpreted as regional functional loss, and broader activation (i.e., greater spatial extent, greater amplitude, or bilateral activation) for older adults compared to younger adults has been interpreted as engagement of compensatory processes. However, predictions of both functional loss and compensatory hypotheses can be more precisely tested by examining individual differences in performance-activation relationships. For example, a functional loss hypothesis predicts that lower performing older adults should show lower regional BOLD signal-change than higher performing older adults (Rypma & D'Esposito, 2001).

In general, cognitive abilities tend to decline with advancing age, but individual differences in the occurrence and magnitude of such declines are known to occur. Age-related declines on measures of WM, visual-spatial reasoning, and processing efficiency have been observed between 20 and 30 year old cohort groups, with further monotonic declines occurring across the lifespan (Park & Hedden, 2001). Variability, however, has been observed in the degree and even presence of age-related cognitive declines: One study, for example, found that about one-third of healthy elderly adults showed age-related memory impairments (Kovisto et al., 1995), and other longitudinal studies have found no detectable age-related cognitive change for up to one-third of the participants tested (Brayne, Huppert, Paykel, & Gill, 1992; Lyketsos, Chen, & Anthony, 1999). The results from the present study suggest that such variation could result from individual differences in the availability of the PFC resources that permit some older adults to maintain functions more than others.

Evidence suggests that processing efficiency declines are a general mechanism leading to age-related declines in many cognitive abilities (see Salthouse, 1996). Median correlations of .45 have been reported between many processing efficiency measures and age (see Salthouse, 1996), including single and composite efficiency measures, mean RTs, time restricted pencil-and-paper tests, and standardized and non-standardized tests, suggesting that processing efficiency is a general factor that declines with advancing age. Additionally, statistical control for measures of processing efficiency has led to reported reductions in the percentages of age-related variance accounted for in a host of cognitive measures. These reductions have ranged from 55% to 91% (see Salthouse, 1996).

According to a processing efficiency theory of age-related cognitive decline, cognitive slowing that occurs with advancing age leads to a cascade of failures that adversely affect the execution of higher-order cognitive functions (Salthouse, 1996). Higher order cognitive processes require timely and complete execution of earlier sub-processes. In this view, age-related slowing leads to (1) time-course discrepancies in the sequence of sub-processes required for successful execution of higher-order cognitive processes, (2) inaccurate or incomplete sub-process computations required for higher-order operations, and (3) increased execution time for higher-order processes because a large proportion of time is spent executing or re-executing sub-processes.

PFC resources (along with those of a broader network) might be necessary to ameliorate the consequences of subprocess execution and completion failures. Younger adults demonstrating greater processing efficiency showed greater PFC neural efficiency, that is, better performance with less reliance on PFC resources than their worse performing younger counterparts. Thus, the present results support the hypothesis that more efficient younger adults are those for whom PFC resources are available to modulate lower-level operations but for whom these resources are not necessary because the lower-level operations function optimally in meeting basic processing requirements of tasks like the DSVT (Rypma et al., 2006). The results also support the hypothesis that less efficient younger adults are those for whom PFC must be committed to coordinate (possibly to control; Shiffrin & Schneider, 1977) sub-process timing and output in order to perform even relatively simple processing efficiency tasks like the DSVT.

The present results also suggest that processing efficiency among older adults depends on PFC resource availability. Older adults demonstrating greater processing efficiency, however, showed less PFC neural efficiency, that is, greater reliance on PFC resources compared to their efficient younger counterparts. Thus, the present results support the hypothesis that more efficient older adults are those for whom PFC resources remain available for coordination of sub-process timing and output and, therefore, for the preservation of cognitive functions in general (Park & Reuter-Lorenz, 2009; Rypma &

Prabhakaran, 2009). The results also suggest that less efficient older adults are those for whom such PFC resources are compromised, and therefore, they are unable to engage the modulatory PFC processes necessary to coordinate the sub-process timing and output negatively affected by advancing age. This pattern of results was obtained even though the older adults in the present sample were in their 50s and 60s, illustrating the robustness of this age-related change.

The present results are consistent with a model in which the differential use of PFC resources for older and younger adults depends on the availability of direct and indirect connections between task-critical brain regions. More efficient younger adults might benefit from direct connections between task-critical brain regions that afford greater reliance on automatic task-execution processes. Skilled task performance has been shown to depend on automatic processes (e.g., Ackerman, 1988), switching from controlled to automatic processes with training, possibly due to the refinement of task-critical functional circuits (Garavan, Kelly, Rosen, Rao, & Stein, 2000). Less efficient younger adults might not have the benefit of refined automatic processes and so must rely more on PFC-mediated controlled processes for the coordination of processing in task-critical brain regions. Age-related automatic processing impairments also have been shown to disrupt acquisition of skilled task performance (Rogers et al., 1994; Hertzog, Cooper, & Fisk, 1996), and studies have shown that processing efficiency accounts for age-related differences in executive function and the effects of age-related executive function declines on other cognitive processes (Crawford et al., 2000). Thus, similar to less efficient younger adults, more efficient older adults might not have the full benefit of automatic processes and must also rely on PFC-mediated resources to coordinate task-critical brain regions. Finally, less efficient older adults might suffer from reduced availability of both PFC-mediated resources (e.g., Rypma et al., 2001; Rypma et al., 2005; Rypma et al., 2007) and automatic processes.

Acknowledgments

The project described was supported by Grant Number AG029523, NS049176, and AG032088 from NIH and Grant Number VA549-P-0027 from the United States Veteran's Administration. The contents are solely the responsibility of the authors and do not necessarily represent the official views of NIH or the Veteran's Administration. The authors would like to thank Ilana J. Bennett and Ehsan Shokri Kojori for comments on earlier drafts of the manuscript and Traci Sandoval, Andrew Hillis, and Kalyan Shastri for their help with data collection.

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1	2	3	4	5	6	7	8	9

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1

Figure 1. Example of stimuli from the Digit-Symbol Verification Task

Participants in the present study completed the digit-symbol verification task while fMRI data were collected. On each trial, a table containing digit-symbol pairs (above) and a single digit-symbol probe (below) appeared simultaneously for 3.5 s, and participants were to judge whether the probe was in the table or not.

Figure 2. PFC voxel clusters in which correlations between percent BOLD signal-change and task performance significantly differed as a function of age-group

A) Colored regions in illustrate PFC clusters of voxels where Performance $\times$ Age-Group interactions were significant based on hierarchical linear regression. Data were cluster thresholded with cluster $\alpha = .05$ and voxel $\alpha = .005$ with t-values ≥ 3.00 . B) Colored voxels illustrate the zRT $\times$ Age-Group interaction effects within the PFC clusters, and C) colored voxels illustrate the zAccuracy $\times$ Age-Group interaction effects within the PFC clusters. Data were thresholded with voxel $\alpha = .05$ with t-values ≥ 2.00 . zRT multiplied by -1 was used in regression so that the color scales for the effects would represent comparable trends in the data.

Figure 3. Percent BOLD signal-change within right and left middle frontal gyri: task performance by age-group interaction effects

Mean percent signal-change estimates, per participant, are plotted as a function of digit-symbol verification task performance for the older (gray lines and open circles) and younger (black lines and closed circles) groups. Signal-change estimates were averaged over voxels showing significant (cluster $\alpha = .05$) group-level Performance $\times$ Age-Group interactions base on voxel-wise hierarchical linear regression, averaging over the two clusters found in right PFC.

Figure 4. Percent BOLD signal-change: task performance and age-group main effects

A) Colored regions illustrate clusters of voxels where BOLD signal-change was significantly linearly related to task performance (cluster $\alpha = .05$). Red to yellow voxels illustrate positive correlations, where better performance was associated with higher signal-change, and blue to cyan voxels illustrate negative correlations where better performance was associated with lower signal-change. (B) Colored regions illustrate clusters of voxels where BOLD signal-change significantly differed between older and younger adults (cluster $\alpha = .05$). Red to yellow voxels illustrate regions where younger adults showed greater signal-change than older adults, and blue to cyan voxels illustrate regions where older adults showed greater signal-change than younger adults.

Table 1

Descriptive Statistics for Clusters Showing (A) Age-Group X Performance Interaction Effects and (B) Performance Main Effects

Anatomical Structure	Coordinates (RAI mm) of Voxels with Highest <i>t</i> -values within Cluster			Number of Voxels in Cluster	Performance Correlations with Mean Percent Signal-Change
	x	y	z		
A) Age-Group X Performance Interaction Effects					
Left Frontal	+25	-41	+26	382	$r_{older} = .79$ $r_{younger} = -.59$
Right Frontal	-33	- 5	+52	404	$r_{older} = .63$ $r_{younger} = -.69$
Right Frontal	-15	-51	+24	158	$r_{older} = .64$ $r_{younger} = -.58$
Left Temporal Pole	+31	-11	-20	719	$r_{older} = .89$ $r_{younger} = -.56$
Right Cerebellum	-35	+49	-36	188	$r_{older} = .77$ $r_{younger} = -.36$
B) Performance Main Effects					
Left Frontal	+47	-23	+24	148	$r_{older} = .65$ $r_{younger} = .62$
Left Middle Occipital	+29	+79	+18	208	$r_{older} = .73$ $r_{younger} = .56$
Left Cerebellum	+41	+51	-26	593	$r_{older} = .74$ $r_{younger} = .67$
Left Cerebellum	+ 9	+39	-48	151	$r_{older} = .70$ $r_{younger} = .63$
Right Cerebellum	-17	+53	-34	188	$r_{older} = .71$

Anatomical Structure	Coordinates (RAI mm) of Voxels with Highest <i>t</i> -values within Cluster			Number of Voxels in Cluster	Performance Correlations with Mean Percent Signal-Change	
	x	y	z			
<hr/>						
Right Cerebellum	- 7	+71	-34	172	$r_{older} = .62$	$r_{younger} = .55$
<hr/>						
					$r_{younger} = .54$	