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When less is more and when more is more: The mediating roles of capacity and speed in brain-behavior efficiency

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Abstract

An enduring enterprise of experimental psychology has been to account for individual differences in human performance. Recent advances in neuroimaging have permitted testing of hypotheses regarding the neural bases of individual differences but this burgeoning literature has been characterized by inconsistent results. We argue that careful design and analysis of neuroimaging studies is required to separate individual differences in processing capacity from individual differences in processing speed to account for these differences in the literature. We utilized task designs which permitted separation of processing capacity influences on brain-behavior relationships from those related to processing speed. In one set of studies, participants performed verbal delayed-recognition tasks during blocked and event-related fMRI scanning. The results indicated that those participants with greater working memory (WM) capacity showed greater prefrontal cortical activity, strategically capitalized on the additional processing time available in the delay period, and evinced faster WM-retrieval rates than low-capacity participants. In another study, participants performed a digit-symbol substitution task (DSST) designed to minimize WM storage capacity requirements and maximize processing speed requirements during fMRI scanning. In some prefrontal cortical (PFC) brain regions, participants with faster processing speed showed less PFC activity than slower performers while in other PFC and parietal regions they showed greater activity. Regional-causality analysis indicated that PFC exerted more influence over other brain regions for slower than for faster individuals. These results support a model of neural efficiency in which individuals differ in the extent of direct processing links between neural nodes. One benefit of direct processing links may be a surplus of resources that maximize available capacity permitting fast and accurate performance.

Keywords

Human brain; functional MRI; cognitive control; executive control

One aim of cognitive neuroscience has been to identify those aspects of neurophysiology that underlie the consistent individual differences in performance that have long been observed in experimental psychology. Spearman's (1904) observation that some individuals consistently

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perform better than others across a broad range of tasks has spawned generations of research investigating the hypothesis that a limited set of resources govern cognitive performance. (Spearman, 1904; Kahneman, 1973; Norman & Bobrow, 1975; Vernon, 1983; Baddeley, 1986; Just & Carpenter, 1992).

The proposal that processing speed is one such resource is based on the notion that individuals differ in the efficiency with which fundamental cognitive operations are performed. Cognitive efficiency theories suggest that when these operations can be performed quickly, resource allocation can be minimized and performance maximized. Efficiency theorists have long hypothesized that correlations between reaction time (RT) and intelligence measures reflected individual differences in “neural efficiency” which permitted some individuals to overcome WM capacity limits (via chunking or other data reduction processes) more than others (e.g., Jensen, 1982, 1998; Vernon, 1983). The advent of modern neuroimaging techniques has made it possible to test such hypotheses by permitting more direct observation of brain-behavior relationships than was possible in the past.

Neuroimaging evidence for neural efficiency

Neuroimaging studies in healthy adults support efficiency explanations of individual differences. Results using electroencephalography (EEG) have shown differences in amplitude and coherence measures that correspond to participants’ performance (e.g., Gevins & Smith, 2000; Reiterer et al., 2005; Grabner, Stern & Neubauer, 2003). In one study for instance, Gevins and Smith (2000) required high ability and low-ability (as measured by WAIS-R performance) participants to perform an n-back working memory task during EEG recording. The important result was that high-ability participants showed less prefrontal, and more parietal activity than their low-ability counterparts. Other EEG studies have measured “event-related desynchronizations” (ERDs) between alpha and theta frequencies that are interpreted as an index of mental effort (Nunez, Wingeirer and Silberstein, 2001). In EEG literature, an ERD is said to occur when the amplitude of one frequency increases while the amplitude of another decreases. These studies have observed reduced ERD in higher, as compared to lower performing individuals (e.g., Grabner, Stern & Neubauer, 2003).

Results from PET and fMRI studies also show reduced activation in faster than in slower individuals (e.g., Haier et al., 1988, 1992; Kosslyn et al., 1996; Larson et al., 1995; Rypma & D’Esposito, 1999; Rypma, Berger & D’Esposito, 2002; Rypma et al., 2005). In one study for instance, Haier et al. (1992) had 8 participants perform a spatial reasoning task, Raven Progressive Matrices. Next, they recorded participants’ glucose metabolic rate (GMR; measured by PET) during performance of a complex visual manipulation task (“tetris”) both before and after extensive practice. In addition to observing GMR reduction after learning, they observed that the extent of GMR reduction was correlated with participants’ scores on the Raven Progressive Matrices. Similarly, Kosslyn et al. (1996) have observed neural activity reductions for faster, compared to slower participants on a mental imagery task. Consistent with these results, Rypma and D’Esposito (1999) observed a significant correlation between participants’ memory search rates and PFC activity. These results suggest a specific model of neural efficiency in which the integrity of structural connections between task-critical brain regions is reflected in PET and fMRI activation. Specifically, they suggest that more direct connections between task-critical brain regions may correspond to decreases in task-related neural activity and improvements in performance (cf. Vernon, 1983; Cerella, 1991; Rypma & D’Esposito, 1999, 2000; Rypma et al., 2006).

Behavioral and neuroimaging studies have yielded results that lend support to an efficiency explanation of individual differences in performance in a broad range of populations. Systematic relationships between juvenile and adult RTs across different cognitive tasks (e.g.,

Keating & Bobbitt, 1978; Kail, 1986, 1988; Kail & Salthouse, 1994) support the notion of a global processing-speed ability governing developmental performance improvements. Such changes have been associated with PFC development (Gomez-Perez et al., 2003), neural activity differences in PFC between children and adults as measured by fMRI (Bunge et al., 2002), and development of PFC white matter as measured by diffusion tensor imaging (Liston et al., 2006).

Systematic RT correlations between younger and older adults have led to the proposal of a global processing speed factor that governs adult-aging performance changes (e.g., Salthouse, 1996b; Cerella, 1991; Hale, Myerson & Wagstaff, 1987). As in child development, age-related processing speed changes have been associated with age-related PFC changes. Such changes appear especially pronounced relative to other regions (e.g., Kemper, 2002; Raz et al., 1997, Raz, 2000; Haug & Eggers, 1991) possibly due to decrements in white-matter (e.g., Peters, 2002; Peters & Sethares, 2004; Madden et al. 2004; Ross et al., 2005). Age-related changes in relationships between neural activity and performance implicate PFC in age-related declines in processing efficiency (e.g., Rypma et al., 1999; Rypma & D'Esposito, 2000; Reuter-Lorenz et al., 2000; Cabeza, 2002; Stebbins et al., 2002; Rypma et al., 2005) and in age-related disease processes (e.g., West, 1996; Medina et al., 2006; Sawamoto et al., 2002; Small, Kemper & Lyons, 2000).

Attenuation of WM performance differences between schizophrenic patients and controls when processing-speed, as measured by DSST, was statistically controlled implicate processing-speed as an important factor in disease-related performance changes (Brebion et al., 1998, 2000; 2008; Jogems-Kosterman et al., 2001; Hartman et al., 2003). Schizophrenics show greater performance decreases, but greater PFC activation increases, relative to controls during WM performance (Callicott et al., 2000). Changes in activation-performance relations have also been observed when healthy control participants are compared to those with multiple sclerosis, a condition with known white-matter impairment, suggests that the integrity of white matter may mediate individual differences in processing-speed (Genova et al., 2008; Lange et al., 2005; Archibald & Fisk, 2000; Vernon, 1983).

Efficiency Explanations of Individual Differences: Divergent Results

Despite the suggestive data and explanatory power of the neural efficiency hypothesis, neuroimaging findings have not consistently replicated across studies. For instance, some studies have shown between-subject performance differences in which greater task-dependent activation was observed in higher than in lower performing individuals (e.g., Newman et al., 2003; Larson et al., 1995; Gray et al., 2003). Mixed results in ERD measurements have been observed as well. For instance, unlike the Grabner et al. (2003) results reviewed above, Klimesch and colleagues have observed greater ERD for higher than lower performing participants (see Jausovec & Jausovec, 2005 for a review).

Similar discrepant results have been reported in PET and fMRI studies. Gray and his colleagues, for instance, performed a study similar to Haier et al.'s (1992; see above) in which, prior to fMRI scanning, participants performed the Raven Progressive Matrices task. During scanning, participants performed a complex WM task in which they viewed single letters that appeared sequentially. They were required to respond each time they observed the appearance of a letter that had also occurred 3 trials earlier. The difficulty of the task was varied by the occasional occurrence of "lure" trials in which a letter repeated either 2, 4 or 5 trials previously. Unlike the Haier et al. (1992) results described above, they observed greater CPT-related neural activity in participants with higher, compared to those with lower, accuracy in Raven performance in a number of different brain regions (see also Callicott et al., 2000; Brand & Deary, 1982; see Toffanin et al., 2007 for further review).

Divergent patterns of activation-performance relations across neuroimaging studies may occur for a number of reasons. In the studies reviewed above, different tasks were employed in the different studies. One possibility suggested by the discrepant results in the Gray et al. (2003) and Haier et al. (1992) studies is that the nature of activation-performance relations may be task dependent. It may be that the n-back task used by Gray et al. (2003) and the tetris task used by Haier et al. (1992) emphasize different cognitive mechanisms. Other studies using similarly complex tasks have also shown divergent results (e.g., Tower-of-London; Newman et al. 2003; Sternberg-type WM; Rypma et al., 1999; backward digit-span; Larson et al., 1995). Indeed, even subtle variations in task parameters have been shown to influence activation-performance relations in both EEG and fMRI studies (Johnson et al., 1997; Rypma, 2006).

We contend that the search for neural mediators of processing efficiency depends upon the tasks and analysis methods employed. The complexity of tasks used in prior studies complicates observation of individual differences in neural efficiency because intersubject variability can be influenced by task-specific demands for, for instance, semantic knowledge, strategy selection, WM storage capacity, processing speed, and other abilities that interact in complex ways and differ between individuals. In one study, for instance, Toffanin and colleagues (2007) instructed higher and lower IQ participants (as measured by the Groningen Intelligence Test; Luteijn & van der Ploeg, 1983) to perform sentence verifications using a difficult “linguistic” strategy or an easy “imagery” strategy during scalp-electrode recording. The important result was that ERD was greater in the linguistic than in the imagery instruction condition, but it did not vary with IQ group. These results illustrate that, when task performance can be mediated by strategy differences, group differences in ability-related neural activity can be minimized. When, however, analyses can be conducted, or tasks can be constructed, so as to isolate (as much as possible) fundamental abilities from task-specific abilities or strategies, then variability resulting from the interplay of multiple cognitive systems can be minimized or decomposed, thereby permitting unobscured observation of individual differences in the neural activity associated with fundamental abilities like processing efficiency.

Dissociating neural efficiency and cognitive strategy

In studies conducted in our laboratories we have used event-related fMRI methods to dissociate components of one cognitive task, the delayed-response WM task. Use of such methods reveals individual differences, not only in neural efficiency, but also in cognitive strategies that individuals use to overcome WM capacity limits.

Neuroimaging research has focused on the role of PFC in the encoding, maintenance and retrieval operations that comprise WM. This focus is based on studies with infrahuman primates performing WM delayed response tasks. In a delayed-response trial, participants are first shown some information that they will be asked to remember at the end of the trial (the “encoding” period). The information is then removed for several seconds, requiring the participant to mentally maintain the information (the “delay” period). Then, in the “retrieval” period, participants are shown some information and asked to indicate whether that information matches that shown in the encoding period. These studies have demonstrated that PFC supports WM by showing WM-specific sensitivity to PFC lesions, and persistent PFC activity during encoding and delay periods of delayed match to sample tasks (e.g., Jacobsen, 1935, 1936; Funahashi, Bruce & Goldman-Rakic 1993; Quintana & Fuster, 1993).

Human WM studies conducted in our laboratories using delayed-response tasks have revealed patterns of activity that are consistent with the neural efficiency hypothesis (Rypma & D’Esposito, 1999, 2000; Rypma, Berger & D’Esposito, 2002; Rypma et al., 2005, 2006). Generally, these studies have indicated less fMRI activity in faster than in slower participants.

In one study participants were required to encode either 2 or 6 letters, maintain them over a delay period, and then retrieve the encoded letters in order to determine whether or not a single letter was or was not part of the encoded memory set. The important result was that, during the retrieval period, large increases in intersubject variability were observed (see Figure 1A). When we attempted to account for this variability by regressing individual participants' PFC activity against their RT slopes, systematic increases in PFC activity were observed with increases in RT slope. This result occurred only in dorsolateral PFC and only in the retrieval period (Rypma & D'Esposito, 1999; see Figure 1B). Across several studies, we and others have replicated and extended these results (e.g., Gevins & Smith, 2000; Rypma & D'Esposito, 2000; Rypma, Berger & D'Esposito, 2002; Grady, McIntosh & Craik, 2003; 2005; Persson et al. 2004; Zarahn et al., 2007; Motes & Rypma, 2008).

Event-related analyses reveal interactions between efficiency and strategy

Systematic manipulation of task factors, and systematic observation of participant factors, in combination with event-related fMRI data analysis, has revealed interactions of processing speed differences between individuals and the strategies they employ to maximize WM capacity. In one follow-up study, we sought to observe individual differences in strategy by increasing task complexity (Rypma, Berger & D'Esposito, 2002). In this study, participants performed a delayed response task in which, across trials, letter strings could vary from 1 to 8. Otherwise, all of the task demands were the same as in earlier studies. There were three important results. First, consistent with prior results, participants' RTs increased with increasing WM load while accuracy decreased. Second, high-performing participants (those performing faster and more accurately than the group median) showed less PFC neural activity than low-performing participants (those performing slower and less accurately than the group median). Third, comparisons of fMRI activation differences between high- and low-performing individuals indicated that, while both groups showed WM load-related activation decreases in ventrolateral PFC at encoding, high-performers showed load-related activation increases in both dorso- and ventrolateral PFC during the early portion of the delay period and the retrieval period. In contrast, low-performers showed such activation increases in dorsolateral PFC only late in the delay period. Thus, while showing overall less activity, high-performers showed activation increases with increasing WM demands over longer periods of time in the task, and in both dorso- and ventrolateral PFC regions, compared to low-performers. These results suggest that the strategies that individual participants employ to maximize WM storage capacity combines with their processing speed to determine performance differences in complex WM tasks.

Our hypothesis is that those participants who exploit the time available in the delay interval to chunk information may effectively reduce WM demand thereby increasing WM capacity and processing speed. Capacity may be defined as the amount of information an individual can hold and manipulate in memory at one time, as measured by digit-span (e.g. Cavanaugh, 1972; Baddeley, 1986; Cowan, 2005). Chunking may be thought of as the strategic binding of individual to-be-remembered items so as to reduce the volume of information, thus increasing WM capacity (e.g., Miller, 1956; Rypma et al., 1999; Prabhakaran et al., 2000; Cowan, 2001; Rypma, Prabhakaran, Desmond, & Gabrieli, 2001; Rypma, et al., 2002; Gabrieli & Preston, 2003; Eldreth et al., 2006; Bor, Duncan, Wiseman, & Owen, 2003; Mitchell, Johnson, Raye, & Greene, 2004; Rypma, 2006).

Experiment 1: The neural basis of strategic processing, WM capacity, and processing speed

We tested this hypothesis using an independent measure of WM capacity, the Digits-forward (DF) portion of the Digit-Span task (Wechsler, 1981). We carried out two experiments, and

employed two analysis techniques to elucidate the brain basis of strategic processing, WM capacity, and WM retrieval speed. We hypothesized that increased activation during the delay interval may reflect greater strategic chunking processes. The result of these processes could be increased WM capacity and processing speed. Thus, we predicted that individual participants' neural activity during WM maintenance would be related to their WM capacity, as measured by DF, and their processing speed, as measured by item-recognition rate.

Method

Participants—Twelve participants (5 females, 7 males, mean age = 19.8) were recruited from the undergraduate and medical campuses of Stanford University. Participants were screened for medical, neurological, or psychiatric illness, prescription medications, and MRI contraindications. All participants were right-handed.

Procedure—Subjects performed a Sternberg - type verbal working memory task (Figure 2E). In the encoding (E) phase of each trial, participants encoded three or six uppercase letters over a 2160 ms interval, followed by a maintenance (M) phase of either 6480 milliseconds or of a short delay of 250 milliseconds. In the retrieval (R) phase, participants were probed with a single lowercase letter and had to judge whether the probe letter corresponded to one of the letters in the encoding set by pressing a yes / no response button. Participants performed a total of four conditions (3 EMR, 6 ER, 3 EMR, 6 ER) in a randomized block design over two sessions. Each block consisted of four trials of a particular condition with a total of six blocks (24 trials) allocated to each condition. Stimuli were generated from a computer (Macintosh G3, Apple Computer, Cupertino, CA) using Psyscope 1.2.1 and back-projected onto a screen located above the subject's neck via a magnet-compatible projector. Stimuli were viewed from a mirror mounted above the subject's head. The sequence of the presentations of the stimuli was synchronized with the imaging sequence of the scanner.

FMRI data acquisition—Imaging was performed with a 1.5T whole-body MRI scanner (General Electric Medical Systems Signa, Rev. 5.3). A custom quadrature receive-only birdcage head coil was used. Head motion was minimized using a bite-bar formed to the participant's dental impression. A T2* sensitive gradient echo spiral sequence (Glover 1996) was used for functional imaging with parameters of TR = 2160 msec, TE = 40 msec, flip angle = 83°, FOV = 20 cm, inplane resolution = 3.125 mm², and sampling interval = 2.16s. Sixteen 7 mm thick slices with a 0 mm inter-slice interval were acquired in the horizontal plane of the Talairach and Tournoux atlas (1988) covering the whole brain.

Analysis Method—Image analysis was performed by transferring the raw data to a Linux machine. A gridding algorithm was employed to resample the raw data onto a cartesian matrix prior to processing with 2D FFT. Each subjects' functional images were motion-corrected and normalized using SPM, interpolated to 2×2×4 mm³ voxels and spatially smoothed with a Gaussian filter (8 mm FWHM). Differences in global signal were removed. Contrast images were created with a fixed effects model, and from which group data were generated via a one-tailed *t* - test. Activation maps were created in SPM.

Results

Behavioral Data—Behavioral results from the first experiment indicated that participants were faster in the 3-letter (mean RT EDR = 987 +/- 43.9 msec; ER = 994 msec +/- 57.0 msec) than in the 6-letter condition (mean RT EDR = 1167 msec +/- 49.6 msec; ER = 1149 msec +/- 30.2 msec). The main effect of WM load on RT was significant, $F(3, 11) = 14, p < .004$, $MSe = 3.37$. Participants' RTs were equivalent in the ER and EDR conditions; the main effect of maintenance duration was not significant, $F < 1$, and the load by maintenance interaction was also nonsignificant $F < 1$.

Participants were more accurate in the 3-letter condition (mean percent accuracy EDR = 95 +/- .5; ER = 93.5 +/- 1) than in the 6 letter condition (mean percent accuracy EDR = 81.6 +/- 1.5; ER = 90.4 +/- .9). The WM load main effect was significant, $F(3, 11) = 15, p < .003$, $MSe = .068$). Importantly, participants were more accurate with a longer delay period. The main effect of delay duration was significant ($F(3, 11) = 6.6, p < .03$, $MSe = .02$) as was the interaction of WM load and delay duration ($F(3, 11) = 6.9, p < .03$, $MSe = .04$).

Across participants, there were significant relationships between DF score and WM retrieval speed in both task conditions (EDR slope = $-26.27, r = -0.77, t = 3.64, p = .004$; ER slope = $-19.011, r = -0.61, t = 2.30, p = .04$). To test the hypothesis that higher capacity participants strategically capitalized on the delay period, we correlated individual participants' RT savings, due to maintenance duration (ER - EDR), with their capacity as measured by DF. RT was affected by delay duration, in the 6-letter, but not in the 3-letter condition. There was a significant positive correlation between participants' RT savings in the 6-letter WM load condition (6ER - 6EDR) and their DF score ($r = 0.58, t = 2.12, p = .05$). No such correlation was found in the 3-letter condition. The hypothesis was supported; high capacity participants appeared to benefit from the longer delay duration possibly because it afforded greater organization for high WM loads and for more efficient retrieval.

FMRI data—FMRI results indicated that a predominantly left hemisphere network consisting of frontal, parietal, and temporal cortex was active among all participants regardless of their WM capacity (see Figure 2A). Individuals with greater capacity showed a proportionate recruitment of right frontal regions with major foci of activity in Brodmann's Areas (BAs) 10 and 46 when maintaining high verbal WM load. The parameter estimate reflects the level of prefrontal recruitment with respect to the capacity of individual participants (Figure 2C). It is worth noting that, consistent with this result, the best performing participants (those with a DF score > 10) showed RT savings while those with lower DF capacity did not. Behaviorally participants conformed to this prediction. Participants with DF scores greater than or equal to 11.9 did show RT savings (DF range=7–13, $M=10.7$).

Experiment 2: Testing relationships between memory capacity and delay-period activity using event-related fMRI

The results of Experiment 1 suggested that participants with greater capacity (as measured by DF) strategically capitalized on the delay-period interval to organize high WM loads for later efficient retrieval. We tested this hypothesis using an event-related fMRI paradigm that permitted separate examination of delay-period PFC activity and its relationship to performance.

Participants

Twelve participants (different from those who participated in Experiment 1; mean age = 20.2, 7 females, 5 males) were screened for medical, neurological, or psychiatric illness, prescription medications, and MRI contraindications. All participants were right-handed.

Procedure

Subjects in Experiment 2 maintained different numbers of letters on different trials (see Figure 2E). Each trial consisted of an encoding phase in which three, four, five, or six letters were presented simultaneously in pseudo-random order for 2.16s (1 frame) followed by a maintenance phase in which the screen was blanked and 6.48s (3 frames) of unfilled delay ensued. This was subsequently followed by a response phase in which a small lower-case letter probe appeared for 2.16s (1 frame) in which subjects confirmed whether the item was part of the letter set that they had seen during

encoding. Subjects made a yes/no response using a keypad with designated buttons for yes and no. This was followed by a 10.8s (5 frames) intertrial interval (ITI). The total duration for each trial was 21.6s (10 frames). Subjects' responses and reaction times (RTs) were recorded and stimuli were presented using Psyscope software on a Macintosh platform. All subjects performed a total of 96 trials over four successive scans with 24 trials per letter load. Prior to scanning, all subjects received a battery of paper and pencil tests including the Digit Span Forward task (DF) outside the scanner.

fMRI data acquisition

Data collection methods were similar to those used in Experiment 1. Reconstructed images were analyzed using SPM (Wellcome Department of Cognitive Neurology, London, England) implemented in MATLAB (Mathworks, Inc., Sherborn). Images were motion-corrected, normalized, spatially smoothed, and filtered similar to those in Experiment 1.

Analysis Method

Single subject data were analyzed with a fixed-effects model. Reference waveforms were created for each temporal phase (i.e. encoding, maintenance, and retrieval) in a trial by convolving a square wave in duration to the specific temporal phase with a standard hemodynamic impulse response function provided in SPM. Cross-correlational analysis was carried out between these reference waveforms and the imaging data set for a particular load and temporal phase. Cortical activation maps were rendered for the encoding, maintenance, and response phases for each of the four memory-load conditions for each subject.

For the group analysis, composite maps were created for the encoding, maintenance, and response phases for each of the four memory-load conditions by averaging the fixed-effect SPM {Z} maps for each of these conditions across all the participants. A linear contrast analysis was done using these averaged maps for encoding, maintenance, and response phases across the four loads in order to identify regions that showed an increase in activation in response to the increase in memory load. Conjunction analyses for the different temporal phases were performed by summing all the effects exhibited in the four loads and eliminating those where there was a significant interaction between the loads. For all analyses, voxels that reached an intensity threshold of $p < .05$ or lower and a spatial extent threshold of $p < .05$ or lower are displayed on each map.

Behavioral Data

Participants' RTs in the single trial experiment were 1103.3 $\pm$ 44.3 ms in load 3, 1151.4 $\pm$ 41.0 ms in load 4, 1197.3ms $\pm$ 42.4 ms in load 5, 1264.6 $\pm$ 53.1 ms in load 6. There was a main effect of load on RT $F(3,11) = 15.4$; $p < .0001$; $MSe = 61330$. Participants were 95.5 $\pm$ 1.6 % accurate in the Load 3 condition, 95.5 $\pm$ 1.7 % accurate in the load 4 condition, 84.3 $\pm$ 2.9% accurate in the load 5 condition, 92.0 $\pm$ 1.5% accurate in the load 6 condition. There was a main effect of load on accuracy $F(3,11) = 12.9$; $p < .0001$; $MSe = 364$.

FMRI data

FMRI data showed similar activity in a left hemisphere network of frontal, parietal, and temporal regions that were shown in the block-design experiment (see Figure 2B). To test our hypothesis of strategic delay-related activity, we correlated participants' delay-related activity with their RT. Those data indicated that individuals with faster retrieval rates recruited a right PFC region (corresponding to BA 10/46) during the 6-letter memory-load condition. Consistent with this observation, there was a positive correlation between individual participants' retrieval slopes and their neural activity during the delay interval (Figure 2D).

Left hemisphere involvement in maintaining verbal information in WM has been demonstrated in previous studies (Rypma et al., 1999; Prabhakaran et al., 2000; D'Esposito et al., 1997). This domain-specific network was observed in all participants (despite their differing DF scores) when maintaining a high WM load (i.e., 6 letters). The additional right PFC regions, utilized by high DF individuals, have been implicated in domain independent (i.e., both non-spatial and spatial) processing in numerous studies. The increased capacity and faster retrieval speed in individuals may be afforded by the activation of these domain independent regions. We hypothesize that these activations reflect binding (i.e., chunking) of to-be-remembered information in the service of increasing WM capacity. This idea is supported by other studies showing activation of these regions during manipulation of to-be-remembered information (see Rypma, 2006 for a review) and integrating multiple forms of information in WM (Prabhakaran et al., 2000; Mitchell et al., 2004; Bor et al., 2003; Eldreth et al., 2006).

Discussion: Experiments 1 & 2

The behavioral results from these studies indicated relationships between participants' capacity (measured by DF) and WM retrieval speed. To examine the brain basis of this relationship, we examined regions that showed increases in activity with increases in capacity during the delay period of a delayed-response task. These analyses indicated a positive relationship between neural activity in right PFC and RT slope. This result suggests that participants benefited from the delay interval, as indicated by (1) the positive correlation between participants' DF scores and their delay-related RT savings, and (2) the stronger negative correlation and steeper slope in the regression of RT slope and DF score in the EDR than in the ER condition.

Together these results suggest that the additional right PFC recruitment in high-span participants during the delay interval reflects strategic processes that, via binding, improve the quality of to-be-remembered information rendering it more available for subsequent retrieval. Indeed, retrieval of individual items from a memory-set is faster and more accurate when items can be searched as a bound unit than when they cannot (Prabhakaran et al., 2000). We observed that only participants with the highest WM capacities (those with DF scores greater than 10) showed right PFC activity as indicated by positive parameter estimates. This observation suggests a processing speed benefit associated with right PFC recruitment.

The event-related method implemented in the second experiment permitted isolation of neural activity related to the delay period and its relationship to participants' retrieval rates. The results of this analysis indicated activity in right PFC regions during the delay that correlated with individual participants' retrieval rates, similar to our earlier results (Rypma, Berger & D'Esposito, 2002; see also Rypma & D'Esposito, 2003). Dorsolateral PFC may support WM processes that permit efficient maintenance and retrieval. It may be that this region mediates information binding in the service of overcoming WM capacity limits (Rypma et al., 1999; Bor et al., 2003; Prabhakaran et al., 2000; Rypma & D'Esposito, 2003; Eldreth et al., 2006).

Our behavioral results, showing that high-span participants' retrieval slopes were diminished with longer delay intervals, suggest that these participants strategically utilized the delay interval between encoding and retrieval to carry out binding operations that effectively reduced WM load. The correspondence between activity in this study and one that explicitly required information binding (Prabhakaran et al., 2000) supports the notion that high-span participants' increased right dorsal PFC activity reflected consolidation processes. To test this idea, we superimposed "capacity-based regions" (i.e., normalized regions whose activity varied with DF score), "speed-based regions" (i.e., normalized regions whose activity varied with retrieval speed), and normalized data from the previous study. Figure 3 illustrates the overlap between capacity-based, speed-based, and binding activation regions. These results have a number of implications. First, the intersection between these two maps provides support for the notion

that increased capacity resources results from strategic consolidation of to-be-remembered information in PFC. Second, they suggest that individual differences in the ability to implement binding (i.e., chunking) strategies may underlie WM performance differences between individuals in both their capacity and speed. Thus, the brain basis of this WM capacity construct involves strategic recruitment of domain-independent regions, (in right dorsal PFC) to effectively compress to-be-remembered data, expand storage capacity, and increase processing efficiency.

Determination of short-term storage capacity limits has been considered essential to understanding human mental architecture (Miller, 1956; Cowan, 2001). Accordingly, the mechanisms available to individuals to overcome capacity limits have been closely studied. The relative availability of these mechanisms between individuals appears to be reflected in WM capacity differences. The present results suggest that some individuals, more than others, utilize domain-independent PFC-based resources. Those who showed more activity in domain-independent binding regions also showed reduced RT slopes compared to those who did not show such activity suggesting more efficient search based on fewer items.

The results of this study suggest that dorsal PFC regions of the right hemisphere mediate strategic WM consolidation processes. The benefits to individuals who implement these strategic processes are increases in WM capacity and processing-speed. Benefits may in turn accrue to higher cognitive processes that depend on WM such as language, text comprehension and reasoning. This mechanism may provide one basis for Spearman's original observation of ubiquitous positive correlations among mental ability measures such as processing speed.

Measuring the neural correlates of processing speed

Our studies of WM delayed response tasks illustrate the use of event-related methods in distinguishing between efficiency-related and task-related variability in neural activity and performance. Increasing task complexity (by increasing the number and extent of WM loads) led to increases in strategy-related variability that influenced participants' performance. When neural activity related to specific task components could be isolated and compared to performance, it was possible to observe those aspects of neural activity related to strategy differences that, in turn, led to performance differences. They also suggest that task-induced strategic processes can complicate straightforward interpretation of relationships between neural activity and performance because individuals vary in the extent to which they employ these processes. Studies that implement relatively simple cognitive tasks (i.e., those that measure a construct or ability directly by minimizing engagement of other processes) may hold the promise of permitting clearer observation of relationships between neural activity and fundamental abilities like processing speed.

In one study (Rypma et al., 2006) we sought to investigate the nature of activation-performance relations in a single task that requires a relatively limited set of cognitive mechanisms thus minimizing the role that strategic processing and WM capacity could play in the results. The DSST may reasonably be said to be such a task as it is considered to measure a unitary construct, namely processing speed (e.g., Salthouse, 1992, 1996a; Wechsler, 1981). First, correlations between DSST and full-scale WAIS scores are high (ranging from .51–.74) and vary little with age (Wechsler, 1981). Second, relations between DSST and performance on other tasks do not appear to depend on other abilities such as motor speed (e.g., Erber, 1976; Salthouse, 1992) or, importantly, WM capacity (e.g., Erber, Botwinick & Storandt, 1981; Fry & Hale, 1996; Jensen, 1998; Salthouse, 1991). Third, it accounts for major proportions of variance in higher-level cognitive tasks including both WM (e.g., Kyllonen & Christal, 1990) and Raven performance (e.g., Ackerman, Beier & Boyle, 2002; Babcock, 1994). Finally, systematic

investigation of strategy accounts in DSST performance has yielded null results (Salthouse, 1992).

Experiment 3: A direct test of the neural efficiency hypothesis

One possibility to explain the divergent results described above is that the nature of activation performance relations may be region-dependent. For instance, Gray et al. (2003) observed significant positive correlations between CPT-related activity and Raven performance in dorsolateral and ventrolateral PFC whereas Haier et al. (1992) observed the greatest correlations between Tetris-related activity and Raven performance in superior PFC regions. Another possibility is that neural efficiency and neural activity are not related in any simple way. Our hypothesis was that those brain regions showing *less* activity with better performance may be functionally related to those regions showing *more* activity with better performance. This study was designed to assess the extent to which individual differences in processing speed are related to neural activity. We sought to observe performance-related variation in neural activity using event-related fMRI in combination with a task with known sensitivity to individual differences in processing-speed, the DSST (Rypma et al., 2006). To articulate the details of this study, we will reiterate its presentation as a separate experiment here.

Method

Participants—Twelve participants (mean age = 22.0, 5 females, 7 males) were recruited from the undergraduate and graduate campuses of Rutgers University, and from the medical campus of the University of Pennsylvania.

Procedure—Participants were first given a standard battery of questionnaires (to determine their MRI compatibility) including a paper and pencil version of the DSST (Wechsler, 1981). It consists of a single page with a code-table of pairings between digits and nonsense symbols at the top of the page. Arrayed down the page are rows of vertically-paired boxes with nothing in the bottom box and a digit in the top box. The participant's task is to write into the bottom box the symbol that goes with digit in the top box, according to the code-table. Participants are given 90 sec to complete as many digit-symbol pairings as possible. Following completion of the questionnaires, participants were trained on the computerized DSST task. Participants were then brought to the neuroimaging suite, given brief practice with the task, and inserted into the scanner. On each fMRI scanning trial, a code-table containing digit-symbol pairs, and a single digit-symbol probe appeared simultaneously for 4 sec. If the probe-pair matched one of those in the table, participants pressed a right-thumb button; otherwise they pressed a left-thumb button (Figure 4E). There were 500 trials in 10 scanning runs. On half the trials, the probe-pair matched one of the digit-symbol pairs in the code table. On the other half, the probe-pair did not match one of the pairs in the code table. RT was measured as the time from the onset of the stimulus (i.e., code-table and probe-pair presentation) to the time that the participant responded. Participants were required to respond within the 4 sec that the stimuli appeared on the screen. Imaging was performed on a 1.5T GE scanner equipped with a gradient echo, echoplanar sequence to acquire data sensitive to blood-oxygen-level dependent (BOLD) signal.

fMRI data acquisition—Imaging was performed on a 1.5 T SIGNA scanner (GE Medical Systems) equipped with a fast gradient system for echoplanar imaging. A standard radiofrequency head coil was used with foam padding to comfortably restrict head motion. High-resolution sagittal and axial T1-weighted images were obtained from every subject. A gradient echo, echoplanar sequence (TR=2000 ms, TE=50 ms, flip angle=65°) was used to acquire data sensitive to the blood-oxygen-level-dependent (BOLD) signal. Resolution was 3.75×3.75 mm in-plane and 5 mm between planes (thus 21 axial slices were acquired). Twenty

seconds of gradient and radiofrequency pulses preceded the actual data acquisition to allow tissue to reach steady state magnetization.

Analysis Method—The event-related design allowed us to examine BOLD signal changes separately for each trial event. Signal changes that occurred during trial events were modeled with covariates comprised of time-shifted, hemodynamic response functions derived from each participant individually (Aguirre et al., 1999). FMRI data were analyzed using the general linear model (GLM) modified to account for serially correlated error terms that result from temporal correlations in BOLD data. Relationships of each trial event with the ITI were assessed by contrasts yielding t-statistics (with ~1195 df) involving parameter estimates and error terms corresponding to the covariates that modeled each trial. T-values for the spatially averaged time series were derived from each ROI for each participant. T-values and RTs were then z-standardized so as to illustrate how scores were distributed around the mean (Hays, 1988).

We tested hypotheses of region-dependence in performance-activation relationships using a specific set of ROIs where these relations have been observed in previous studies. Restriction of analyses to these brain regions increased statistical power to detect effects. Data analyses were performed in 8 ROIs across the 2 hemispheres, dorsolateral PFC (BA9) posterior PFC (BA46), ventrolateral PFC (BA44) and parietal cortex (BA40).

Granger Causality methods were used to study dynamic interactions between cortical regions. Granger Causality between two regions can be defined as the extent to which data from one region at one point in time improves the prediction of another region's data at a later point in time (Goebel et al., 2003). Analyses were performed by first extracting time-series from each ROI. Each time-series was fit using a full vector autoregressive model. We used a 5th order vector autoregressive process to test the significance of influences between ROIs. In this process, five time points (10 sec) from one ROI time-series were sequentially omitted and its effect in predicting the output of another ROI time-series was calculated. Sub-model fits were then performed for each regional time-series compared with those of all other regions. Thus, time-point omission from one regional time series permitted characterization of its influence on other subsequent time points in other regional time series.

Submodel fits and directional causality was tabulated for each of the time-series data sets. Model diagnostic tests and resulting significance levels were estimated from the sub-model fit matrix (Goebel et al. 2003) and were based on within-group significance levels. Directed influences between the different regions were tabulated for two different significance levels (0.05 and 0.10). Influences were considered significant for $p < .05$. They were considered trends when $.05 < p \leq .10$. Causality matrices between the different regions were obtained from slower and faster participants (separated by median DSST performance) and grouped together. Element-wise differences between faster and slower groups were calculated to find inter-regional differences between them. The differences obtained were mapped onto a schematic axial brain illustration from the Talairach and Tournoux (1988) atlas.

Results

Behavioral data—Behavioral analyses indicated uniformly high accuracy with minimal interindividual variability ($M=97.0\%$, $SD=.01$). RTs were fast with more variability (1331.5 msec, $SD=177.4$) than in accuracy data. FMRI analyses indicated activation in a network of PFC and parietal regions across participants. There was considerable interindividual variation in the location and spatial extent of these BOLD changes.

FMRI data—Strong relationships between regional cortical involvement and response speed were also observed. Figure 4A shows regional activation in the fastest participant and slowest

participant. In PFC, BOLD effects in the slowest participant showed a greater spatial extent than in the fastest while the opposite effect appeared in parietal cortex. Regression analyses of individuals' z -standardized mean RT and regional BOLD signal change, as measured by spatially-averaged t -statistics (Figure 4B), characterized activation-performance relationships in different brain regions. Dorsolateral PFC (BA9) showed a significant positive correlation (slope = .88, $r^2 = .77$, $p < .01$), consistent with neural efficiency explanations of performance speed. Posterior PFC regions (i.e., BA46) showed no such relationship. Significant negative correlations were observed in ventrolateral PFC (BA44; slope = -.76, $r^2 = .39$, $p < .03$) and parietal regions (BA40; slope = -.76, $r^2 = .58$, $p < .004$). Similar results were obtained when we analyzed parameter estimates using resampling methods indicating that these results did not depend on error in fMRI signal measurement and were robust to the power limitations of this low N design (Rypma, Eldreth & Rebbechi, 2007).

These results indicated that the relative speed of individuals' performance varied with the activity of specific brain regions. As can be seen in Figure 4B, the nature of these activation-performance relationships varied across brain regions. RT increases were related to increased dorsolateral PFC involvement, but decreased ventrolateral PFC and parietal involvement. Using Granger analyses, we directly tested the hypothesis that, among slower individuals, PFC (possibly executive) systems guide posterior systems. Using Granger we characterized the strength and direction of influence between discrete brain areas by measuring the extent to which activation changes in one region reliably preceded those in other regions (Goebel et al., 2003).

Figure 4C shows results of the Granger Causality analyses superimposed on standard axial slice ($z = +28$) illustrations. Influences were aggregated for faster (4 M, 2 F, M age = 23) and slower (3 M, 3 F, M age = 23) groups, as indicated by DSST RT. Arrows indicate significant influences (red = $p < .05$; yellow = $p < .10$). There were three differences between faster and slower participants. First, slower participants had more interregional influences than faster participants (Mann-Whitney test $p = .02$). Second, slower participants had more frontal-to-parietal influences than faster participants. To test this observation, we regressed individual participants' RTs upon the number of BA9 influences extending to other ROIs. Slower participants showed more BA9 influences (Figure 4D; note some points overlap). The standardized regression coefficient was significant (slope = .77; $R^2 = .60$; $p < .003$). Third, we observed more reciprocal connections between BA9 and other regions for slower than faster participants. We tested the possibility that, between participants, an increase in the number of regions upon which BA9 exerted influence corresponded with an increase in the number of regions influencing BA9 in return. We calculated for each participant a "reciprocity index" by multiplying the number of BA9 influences on other regions by the number of influences on BA9. This index yields maximal values as the number of BA 9 influences approaches the number of influences on BA9. Deviations away from this reciprocity yield smaller values. A Mann-Whitney test indicated greater BA9 reciprocity values for the slow (median = 1.5) than for the fast group (median = 0.56; $p = .008$).

Discussion: Experiment 3

These results support the hypothesis that individual differences in cortical function are associated with individual variability in processing speed. We observed considerable variability both in individuals' DSST performance and in their neural activity in a frontoparietal network that has been associated with WM (e.g., Curtis & D'Esposito, 2003; D'Esposito, Postle & Rypma, 2000) and reasoning (e.g., Prabhakaran et al., 1997; Prabhakaran, Rypma & Gabrieli, 2001; Haier et al., 1988) and whose activation is known to vary with differences in performance (e.g. Maccotta & Buckner, 2004; Nobre et al., 2003; Poldrack et al., 1998).

Granger causality relationships between brain regions suggested that there was overall more interregional connectivity in slower participants than in faster participants, suggesting that efficient interregional communication provides the neural basis of processing speed. Moreover, there were more influences directed from dorsolateral PFC to other regions for slower than for faster participants. Thus, these results also suggested that the extent and direction of influences between brain regions underlies cognitive efficiency and individual differences in performance.

Region-dependent relationships between neural activity and performance

Our results suggested that different brain regions showed different relationships to RT. Dorsolateral PFC regions showed increases in neural activity with increases in RT. These results support and extend earlier results from our WM studies detailed above (see also Rypma & D'Esposito, 1999; Rypma, Berger & D'Esposito, 2002; Narayanan et al., 2005) by suggesting that processing speed differences between individuals may not be due to functional differences in one specific region, but rather the nature of the connectivity between task-relevant brain regions. Thus, whereas dorsolateral PFC activity decreased with increased processing speed, activity in parietal and ventrolateral PFC regions increased with increased processing speed. This region-dependent pattern of activation-performance relations suggests that neural efficiency may be related to both increases and decreases in regional activity.

The region-dependent nature of these activation-performance relationships also suggest support for the parietal-frontal integration theory advanced by Jung and Haier (2007). That theory proposed that individual variations in intelligence depend on variations in interactions between PFC and parietal cortex. Our results extend this model by suggesting that optimal performance occurs when posterior brain regions (parietal cortex and ventrolateral PFC in the case of the visual-search processes associated with DSST) can operate with minimal executive dorsolateral PFC control. Slower performance occurs when greater dorsolateral PFC involvement is required to provide top-down control of task-relevant brain regions. Results from the present study showing more dorsolateral PFC influences upon other brain regions for slower as compared to faster performers supports this hypothesis (see also Prabhakaran & Rypma, 2007). Our results suggest that these influences are reciprocal. The reciprocity index results indicated that the more dorsolateral PFC influenced other regions, the more those regions interacted with dorsolateral PFC in return. Thus, it may be that processing speed is mediated, not only by increased executive control, but also by increased executive monitoring. Monitoring functions have been associated with PFC in neurophysiology, neuroimaging, and neuropsychology studies (e.g., Muller & Knight, 2006; Rajah & McIntosh, 2006; Petrides, 1995). Together the present results support the idea that relatively slower adults may require more PFC executive control for optimal performance than faster participants. Faster adults may depend less on controlled processing. These individuals may instead rely upon more automatic processing based in domain-dependent posterior brain regions (e.g., Shiffrin & Schneider, 1984; Rypma et al., 2006; Prabhakaran & Rypma, 2007).

General Discussion: Neural mechanisms of processing capacity and efficiency

The studies we have presented here demonstrate the contributions that individual differences in cognitive capacity and processing-speed make to fMRI variability. Comparison of two kinds of studies (one involving relatively complex WM delayed-response tasks and one involving relatively simple processing-speed tasks) indicate that the contribution that capacity differences and speed differences make to fMRI variability depends on the task under study.

Increasing task complexity by increasing WM-load requirements induced participants to implement strategies in the course of task performance. Results from our blocked and event-related delayed response tasks indicated that some participants utilized the delay interval more than others to perform additional processing of to-be-remembered information. Overlap analyses suggested that the load-related delay-period activity we observed in dorsolateral PFC regions may reflect binding operations that permit more efficient maintenance and retrieval (see also Eldreth et al., 2006). It may be that participants with relatively higher capacity are those participants who implement more efficient strategies in WM relative to those with lower capacity (cf. Larson et al., 1995; Gevins & Smith, 2000; Eldreth et al., 2006; Toffanin et al., 2007). More research is certainly needed to distinguish between effects that result from individual differences in neural efficiency and those that result from strategic differences that maximize WM capacity.

We minimized the role of individual strategy and WM capacity differences through the use of a simple processing speed task. Our results suggest that individual differences in cognitive performance reflect fundamental differences in PFC activity (possibly reflecting differences in the extent of PFC control required for optimal performance). The finding in this study, that relative increases and decreases in BOLD activity are intimately linked to regional connectivity, implicates a central role for axonal structures in interindividual activation differences. It may be that the efficiency of neural interconnections reflects differences in white-matter integrity. Anatomical studies have shown individual differences in both white- and gray-matter that could mediate interactive activation changes between brain regions and participants' processing-speed performance (e.g., Haier et al., 2004, 2005; Madden et al., 2004).

The results of Experiment 3, region-dependent and interactive activation tied directly to individual participants' processing speed performance, are consistent with neural efficiency hypotheses (e.g., Vernon, 1983; Haier et al., 1988; 1992; Cerella, 1991; Rypma & D'Esposito, 2000). We have proposed a specific model of neural efficiency based on the idea that cognitive task performance requires transmission across an array of interconnected nodes (e.g., McClelland, Rumelhart & Hinton, 1986; See Figure 6). Nodes may represent individual neurons or functionally connected cell-assemblies (e.g., Hebb, 1949). Nodes may be connected by pathways that correspond to axonal processes. Greater internodal transmission may lead to greater neural activity, but slower processing. When fewer nodes can be traversed, (Figure 5A) processing paths are more direct, neural activity is reduced, and information processing is faster. When the integrity of direct processing links between nodes is reduced (Figure 5B), more indirect links must be traversed, neural activity is increased, and information processing is slower.

We have demonstrated results suggesting that this model can account for population differences in brain-behavior relationships. For instance, advanced aging and disease could result in further decrements in processing links, (Figure 5C), further reductions in available nodes, decreases in neural activity, and further decreases in processing speed. Data we have collected with healthy older adults in WM studies support this hypothesis by showing that faster older adults show greater PFC activity than slower older adults (e.g., Rypma & D'Esposito, 2000; Rypma, Eldreth & Rebbeschi, 2007). We have recently replicated these findings in a comparison of older and younger participants performing the DSST during fMRI scanning. All of the task parameters were identical to those described above (Motes, Biswal & Rypma, 2008; see Figure 6). We have observed similar changes in brain-behavior relationships when DSST-related activity in MS patients is compared to healthy controls (Genova et al., 2008).

In this series of studies we have shown that individual differences in performance of complex WM delayed response tasks and simple processing speed tasks are associated with differences

in PFC activity, as measured by fMRI. Increased delay-period PFC activity was associated with faster performance whereas increased DSST-related PFC activity was associated with slower performance. This pattern of results provides important clues to understanding the complex pattern of results that has been observed so far in studies of individual differences in neural efficiency. Whereas considerable behavioral research has been done investigating the relative primacy of processing capacity and processing speed in determining individual performance differences (e.g., Kail & Salthouse, 1994; Fry & Hale, 1996; Salthouse, 1996a; Cowan, 1998; Ackerman, Beier & Boyle, 2002; Conway et al., 2002), few neuroimaging studies have addressed this issue. More research is certainly needed but the present results suggest that the relative primacy of one ability or another may be dynamic, depending on properties of the participant sample and the nature of the task at hand.

The present results are consistent with the hypothesis that complex tasks induce participants to formulate chunking strategies that minimize WM demand, maximize WM capacity, improve performance, and reduce neural activity for better performers (e.g., Gevins & Smith, 2000; Rypma, Berger & D'Esposito, 2002; Toffanin et al., 2007). Use of a simple task that was maximally sensitive to processing-speed and minimally sensitive to strategy (e.g., Erber, 1976; Erber, Botwinick & Storandt, 1981; Salthouse, 1996a; Joy, Fein & Kaplan, 2003; Rypma et al., 2006), revealed that increased PFC activity was associated with slower performance. This pattern of results is consistent with the hypothesis that the efficiency of PFC connections to other brain regions (possibly reflecting axonal or white-matter integrity) mediates performance speed. It may be that those individuals identified as faster performers on a processing speed task are those who benefit from fast direct connections between brain regions. Such efficient connections may permit maximal performance while minimizing resource allocation. A surfeit of processing resources could facilitate WM storage capacity, formulation of optimal task-specific strategies, and minimize the neural activity required to perform complex tasks like the WM delayed-response task.

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Figure 1.

A. Results from Rypma & D'Esposito (1999) showing increased variability in dorsal PFC during WM retrieval relative to other task periods; open bars indicate results for 2 letter condition, dark bars indicate results for 6 letter condition. B. Scatterplot of dorsal PFC activity plotted against individual participants' RT slopes. Black line indicates results for dorsolateral PFC, red line indicates results for ventrolateral PFC

Figure 2.
A. FMRI results of the contrast of 6-letter EDR vs. 6-letter ER conditions in the block-design study. B. FMRI results of the contrast of delay-period activity in the 6-letter condition vs. baseline (ITI). Activity common to all participants is color-coded in green, activity varying with individual differences in DF score is color-coded in red). Images show regions that were significantly more active ($p < .001$, corrected). C. FMRI activation in right PFC during delay period plotted against DF score. Participants with greater capacity showed greater activation in this region. D. FMRI activation in right PFC during delay period plotted against RT slope. Participants with faster processing rates showed greater activation in the right PFC region. A full listing of Talairach coordinates can be found at

www.utdallas.edu/research/nprlab/research.htm E. Schema of verbal delayed-recognition tasks during blocked and event-related fMRI scanning. In the Block Design study, participants encoded 3 or 6 letters and maintained items over a delay interval of 6480msec vs. 500msec. In the Event-related study, participants encoded 3, 4, 5, or 6 letters and maintained over a delay interval of 6480 msec. In both of the studies participants responded in the retrieval phase with a 'yes' or 'no' response to confirm whether they had seen the letter during encoding.

Figure 3.

Overlap analysis. High memory load delay period activity varying with individual participants' capacity (i.e., DF score) is coded in blue. High memory load delay period activity varying with individual differences in retrieval rate is coded in red (Narayanan, et al., 2001). Delay period activity while maintaining bound (vs. unbound) information in memory is coded in green (Prabhakaran et al., 2000). The centroid of maximum foci in all 3 maps corresponds to Talairach coordinates of 35, 28, 24 (see www.utdallas.edu/research/nprlab/research.htm for a table of all activation coordinates in Experiments 1 and 2).

Figure 4.

A. Cortical activity in the fastest and slowest individuals in an ROI showing less activity for the fastest than for the slowest individual (BA9, dorsolateral PFC) and in an ROI showing more activity for the fastest than for the slowest individual (BA40, parietal cortex), indicating region-specific brain-behavior relationships. B. Results of regression analyses between ROI-wise cortical activity and RT. Scatterplots show standardized mean t -values for each individual plotted against their standardized RTs. C. Results of Granger Causality analyses between prefrontal (BAs 9, 46 and 44) and parietal (BA 40) regions superimposed on an axial slice ($z = +28$) illustration taken from a standard atlas. Influences were calculated separately for faster and slower individuals (grouped by median split; arrows indicate significant influences);

red= $p < .05$; yellow = $p < .10$). D. Scatterplot of the number of BA9 influences on other regions plotted against individual participants' RTs (note some points overlap). E. Schema of DSST: On each fMRI scanning trial, a code-table containing digit-symbol pairs, and a single digit-symbol probe appeared simultaneously for 4 sec. If the probe-pair matched one of those in the table, participants pressed a right-thumb button; otherwise they pressed a left-thumb button

Figure 5.

A model of neural efficiency based on the integrity of processing links between nodes. A. When fewer nodes can be traversed, processing paths are more direct, neural activity is reduced, and information processing is faster. B. When the integrity of direct processing links between nodes is reduced, more indirect links must be traversed, neural activity is increased, and information processing is slower. C. Further decrements in processing links, as may occur in aging and disease, lead to reductions in available nodes, decreases in neural activity and further decreases in processing speed.

Figure 6.

Results of hierarchical regression analysis showing dorsolateral PFC (DLPFC) percent signal-change in younger (N=15) and older (N=15) adults performing the DSST. Significant correlations between RT and percent signal-change (yellow=positive, blue=negative relationships) are displayed for (A) older and (B) younger groups. Faster and more accurate older participants showed greater task-related DLPFC signal-change than their slower and less accurate counterparts. Faster and more accurate younger participants showed less task-related DLPFC signal-change than their slower and less accurate counterparts. C. There were significant Age-Group X Performance interactions in several DLPFC regions (orange).