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The neural bases of the effects of item-nonspecific proactive interference in working memory

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We reanalyzed the behavioral and fMRI data from seven previously published studies of working memory in order to assess the behavioral and neural effects of item-nonspecific proactive interference (PI; attributable to the accrual of antecedent information independent of the repetition of particular items). We hypothesized that item-nonspecific PI, implicated in age-related declines in working memory performance, is mediated by the same mechanism(s) that mediate item-specific PI (occurring when an invalid memory probe matches a memorandum from the previous trial). Reaction time increased across trials as a function of position within the block, a trend that reversed across the duration of each multiblock experiment. The fMRI analyses revealed sensitivity to item-nonspecific PI during the probe epoch in the left anterior inferior frontal gyrus and the left dorsolateral prefrontal cortex (PFC). They also revealed a negative trend, across trials, in the transient probe-evoked component of the global signal. A common PFC-based mechanism may mediate many forms of PI.

Working memory refers to the cognitive capacity that enables the temporary on-line maintenance and manipulation of information when that information is no longer present in the environment. Because working memory has been implicated as a critical contributor to such complex cognitive abilities as language comprehension, learning, planning, reasoning, and general fluid intelligence (Baddeley, 1992; Engle, Kane, & Tuholski, 1999; Jonides, 1995; G. A. Miller, Galanter, & Pribram, 1960), understanding the factors that govern its success or failure under various conditions is an important goal of cognitive neuroscience. Although the causes of forgetting in working memory are not fully understood, decades of psychological research indicate that interference (more so than, for example, decay associated with the mere passage of time) is an important factor. Thus, Keppel and Underwood (1962) famously demonstrated that there is virtually no forgetting on the first trial of the Brown–Peterson task, regardless of the length of time separating target presentation from response, but that errors are already present on the second trial, even at the shortest of delays. And Wickens and colleagues have established that proactive interference (PI)—the disruption of performance on a memory task attributable to antecedent information—need not be produced by the repeated presentation of one or more particular items but that it is also present if items from preceding trials are drawn from the same class of stimuli (e.g., letters or digits; Wickens, Born, & Allen, 1963) or from the same semantic category (in the case of nouns), or even if they are simply presented with similar perceptual characteristics (e.g., letter case, modality, figure/ground, or slide area; Wickens, 1973). The present study represents an initial step in our effort to understand the cognitive and neural bases of interference mediation in working memory.

Recently, two accounts have emerged that link interference mediation with a specific control process (inhibition; Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999) and with a specific neural locus (left inferior prefrontal cortex [PFC]; Jonides, Badre, Curtis, Thompson-Schill, & Smith, 2002; Jonides, Smith, Marshuetz, Koeppe, & Reuter-Lorenz, 1998). In the former account, Hasher and colleagues postulated that there is a *deletion* or *suppression* mechanism that protects items represented in working memory from the degrading effects of PI. To support this view, they showed that the working memory span performance of neurologically healthy elderly individuals can be enhanced if steps are taken to minimize the carryover of PI from previous trials (Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999). In the latter account, Jonides and colleagues employed a modified Sternberg item recognition task in which a large proportion of invalid probes, although they did not match any memoranda from the current trial, matched a memorandum from the preceding trial (Monsell, 1978). Such *high-overlap* probes create a situation in which the correct response is *no*, but in which correct rejection of the probe may be more difficult because of its similarity to the item from the previous trial. Responses to high-overlap probes

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are associated with longer reaction times (RTs) and greater activity in Brodmann's Area (BA) 45 of the left inferior PFC (D'Esposito, Postle, Jonides, & Smith, 1999; Jonides et al., 2002; Jonides et al., 2000; Jonides et al., 1998; Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003). Although these two accounts were developed to address different empirical phenomena, there are reasons to speculate that they may relate to similar cognitive and/or neural mechanisms. Among these are the fact that inhibition has also been considered a candidate mechanism underlying the PI effect in the left inferior PFC (Jonides et al., 1998), the fact that aging is associated with declines in performance in both working memory span tasks (Lustig et al., 2001; May et al., 1999) and high-overlap conditions of the item recognition task (Jonides et al., 2000), and the fact that age-related decline in PFC function (e.g., Glisky, Polster, & Routhieaux, 1995; Moscovitch & Winocur, 1995; Raz et al., 1997; Warren, Butler, Katholi, & Halsey, 1985) might explain the age-related sensitivity to PI that is central to the inhibition account (Lustig et al., 2001; May et al., 1999). Thus, one goal of the present study was to assess whether the unification of the theoretical account of Hasher and colleagues and the neural account of Jonides and colleagues might be a fruitful direction for future investigations of the control of PI in working memory.

One important difference between the two research programs summarized in the previous paragraph is that they have focused on PI that arises from two different sources. High-overlap probes in the item-recognition task produce item-specific PI, whereas the inhibitory account relates to item-nonspecific PI. Item-specific PI occurs when the response-eliciting probe on the current trial matches an item not from the current memory set (and thus, the correct response is *nonmatch*), but from the memory set of the previous trial. (Wickens et al., 1963, referred to this as *formal similarity*.) An implication of this is that the PI resolution mechanism(s) studied by Jonides and colleagues is only engaged phasically, after the onset of the probe stimulus reveals its formal similarity with a memorandum from a previous trial (D'Esposito et al., 1999). Item-nonspecific PI, in contrast, develops as the number of items presented during a testing session accumulates, with or without formal similarity among items from different trials (Keppel & Underwood, 1962; Wickens, 1973; Wickens et al., 1963). Although the precise factors underlying this phenomenon remain unclear, overlap of the representations of memoranda from different trials and/or weakening of the contextual tags linking specific representations with particular trials are candidate explanations. Stated generically, item-nonspecific PI lowers the signal-to-noise ratio of the contents of working memory.

Any number of mechanisms might accomplish the inhibitory control proposed by Hasher and colleagues (Hasher & Zacks, 1988; Hasher et al., 1999). Examples include a tonic suppression mechanism that drapes a steady cloak of inhibition on all no-longer-relevant representations, a phasic deletion mechanism that actively removes representations from working memory upon completion of a trial, or a phasically deployed "shield" that is recruited with the onset of the probe to insulate it and/or the currently relevant memoranda from PI while probe evaluation operations (e.g., exhaustive serial memory scan [Sternberg, 1966] or diffusion-based retrieval [Ratcliff, 1978]) are underway. The latter two could have a time course similar to that observed in studies of item-specific PI. (Note that, although Hasher and colleagues have emphasized inhibition in their account, the control of PI need not rely on top-down inhibition [e.g., Bunge, Ochsner, Desmond, Glover, & Gabrieli, 2001; Jacoby, Debner, & Hay, 1991; Kimberg & Farah, 1993, 2000; MacLeod, Dodd, Sheard, Wilson, & Bibi, 2003; E. K. Miller & Cohen, 2001], a consideration that we will revisit in the General Discussion section.)

This research was undertaken to investigate the neural and behavioral correlates of item-nonspecific PI in working memory. To our knowledge, there has been little study of the neurophysiological correlates of this phenomenon. One possibly related phenomenon, an item accumulation effect, has been observed in two previous studies of updating in working memory: PFC activity, as measured by ERP (Kiss, Pisio, Francois, & Schopflocher, 1998) and fMRI (Postle, Berger, Goldstein, Curtis, & D'Esposito, 2001), increased monotonically as more and more items were presented in a single trial. (Note that this was not a simple load effect, because the participants maintained a constant span of four items throughout each trial.) In the fMRI study, this effect was seen throughout the PFC (i.e., it was not localized to any subregion). Because neither of these studies looked at cumulative effects across trials, the relation of this item accumulation effect to item-nonspecific PI is unclear. An alternative is that the item accumulation effect may reflect the operation of control processes that govern the updating of working memory.

EXPERIMENT 1

We reanalyzed the fMRI and behavioral data from several previously published studies of working memory, coding trials by position within the block, rather than according to the independent variables that were used to implement the hypothesis tests for which these tasks were originally developed. We realized that a sample such as ours, assembled from a heterogeneous set of studies, would be expected to be noisy with respect to the factor of interest in this reanalysis. Our rationale for undertaking this study, however, was that the low sensitivity inherent in this approach might be sufficiently offset by the relatively large size of our sample, so that our efforts might yield some insights about item-nonspecific PI. Our approach was to restrict ourselves to testing for simple trends that would answer basic questions about item-nonspecific PI and, perhaps, sharpen our ideas about possible commonalities between the mental pro-

cesses governing the control of it and of item-specific PI. The principal goal of this study was to determine whether the sensitivity of activity in left BA 45 to the buildup of item-nonspecific PI is different from that in other subregions of the PFC (i.e., does it resemble its sensitivity to item-specific PI in this respect?). This question was critical, because a necessary—although not sufficient—piece of evidence that two tasks engage a common mental process is that they activate a common region of the brain. A second question that we planned to address related to mechanism: Does the item-nonspecific PI effect in left BA 45 manifest itself in a phasic, probe-locked manner, as does the item-specific PI effect? This second question reflected the fact that the most straightforward prediction of a common-processes model is that the dynamics of the mediation of item-specific PI and item-nonspecific PI would be the same. (There were, of course, other alternative architectures that could also reflect the operation of a common mechanism. One such alternative was that item-nonspecific PI may be mediated by a tonically active mechanism whose function can be further increased in a phasic manner when item-specific PI is detected. In this alternative scenario, one would expect sensitivity of BA 45 activity to item-nonspecific PI to be present during all the epochs of a trial, and not just during the probe.) We also examined sensitivity to item-nonspecific PI in the anterior cingulate cortex (ACC), because its role in conflict resolution (reviewed by Jonides et al., 2002) made it a candidate for a role in PI resolution as well.

Method

Participants

Behavioral data from 34 right-handed adult participants and fMRI data from 25 of these same participants were reanalyzed in our experiment. The 25 participants whose behavioral and fMRI data were reanalyzed had participated in one of five previously published studies (Postle, Berger, & D'Esposito, 1999; Postle et al., 2001; Postle, Berger, Taich, & D'Esposito, 2000; Postle & D'Esposito, 2003; Postle, Druzgal, & D'Esposito, 2003), and the remaining 9 participants whose behavioral data were reanalyzed had participated in one of two other studies (D'Esposito et al., 1999; Postle & D'Esposito, 1999). Due to technical problems, the fMRI data from the latter two studies could not be reanalyzed. None of the participants reported any medical, neurological, or psychiatric illness or taking any prescription medication. All gave informed consent.

Materials

Three of the studies employed letters as stimuli (D'Esposito et al., 1999; Postle et al., 1999; Postle et al., 2001), three employed spatial locations (presented either on an otherwise featureless background [Postle & D'Esposito, 1999, 2003] or by highlighting elements in an array [Postle, Berger, et al., 2000]), one employed Attneave shapes (Postle & D'Esposito, 1999), and one employed grayscale faces (Postle et al., 2003; see Table 1).

Procedure

Behavioral data from seven studies (D'Esposito et al., 1999; Postle et al., 1999; Postle et al., 2001; Postle, Berger, et al., 2000; Postle & D'Esposito, 1999, 2003; Postle et al., 2003) and fMRI data from five of these studies (Postle et al., 1999; Postle et al., 2001; Postle, Berger, et al., 2000; Postle & D'Esposito, 2003; Postle et al., 2003) were reanalyzed in the present experiment. Because the specific procedures associated with each task are presented in detail elsewhere, we will only briefly describe their generic trial structure here. All the trial types are listed in Table 1. All but one of the tasks were variants of delayed item recognition, in which the trial began with the presentation of memoranda (target epoch), followed by a delay period of 7 or 8 sec (delay epoch), followed by a memory probe that required a *yes* or *no* response with a buttonpress (probe epoch). One of the delayed-recognition studies (Postle et al., 2003) employed an ABBA design in which several trials featured two or three delay periods. For the purposes of the present reanalysis, we collapsed across multiple delay periods from such trials, so that each trial contributed one delay epoch data point. The sole exception to the standard delayed-recognition procedure was a running memory span, or *updating*, task, in which one to three items were presented during each of two to eight stimulus presentation epochs (separated by a stimulus onset asynchrony [SOA] of 4 sec). In the course of a trial, participants kept in memory the four most recently presented items and assessed the validity of the memory probe (with a Y/N buttonpress) that appeared unpredictably with an SOA of 4 sec (Postle et al., 2001). For the purposes of the present reanalysis, stimulus presentation epochs from the updating task were treated as delay epochs.

In all of the studies except the one employing face stimuli (Postle et al., 2003), the pools of stimuli were sufficiently small that each stimulus appeared several times within each block, although all employed a stimulus selection algorithm of random or pseudo-random selection without replacement, so as to create maximum spacing of repetitions (the exception was the study of item-specific PI; D'Esposito et al., 1999). Such stimulus repetition was not expected to create a confound of item-specific with item-nonspecific PI, however, for two reasons. First, item-specific PI is defined as the situation that arises when the probe from trial n matches a memorandum from trial $n-1$. Second, it has been established that item-nonspecific PI is insensitive to the repetition of specific items across trials (Wickens et al., 1963). Nevertheless, we also examined behavioral data from the *face* study (Postle et al., 2003) separately, to determine whether item-nonspecific PI effects were also seen in a task in which no item appeared in more than one trial of the entire experiment.

Analyses

The logic of the present experiment was to reanalyze the data from these studies, with position within the block as the principal factor of interest, rather than the factors that were of theoretical interest in the original experiments (Table 1). To accomplish this, the data were recoded according to a trial's position within the block, collapsing across experimental condition and across blocks. In this way, we sought to detect a trend that evolved across time, so that its effect for any 1 trial would be a function of the number of antecedent trials in the block. Six of the experiments that were reanalyzed featured 12 trials per behavioral block (with each block corresponding to a scan). For the one experiment that featured 16 trials per block (Postle & D'Esposito, 2003), the data from the final 4 trials from each block were discarded from all the analyses. Most single-participant data sets from all seven experiments contributed eight blocks of data, although a few individual data sets had fewer than eight, either because a scanning session was terminated prematurely or because data from one or more scans were corrupted. One participant from D'Esposito et al. (1999) contributed nine blocks of data. Thus, there were typically eight observations per trial position per participant.

Note that, because trial order had been randomized according to factor of interest in each of the original experiments, our method necessarily produced noisy data sets. For example, we could not control, for a particular block in Postle et al.'s (1999) study, the order in which *Forward 2*, *Forward 5*, and *Alphabetize 5* trials oc-

Table 1
Summary of Trial Types and Stimulus Material From the Seven Studies Reanalyzed in the Present Experiment

Study	Trial Type	Stimulus Material
D'Esposito, Postle, Jonides, & Smith, 1999*	Delayed item-recognition, item-specific PI present	letters
	Delayed item-recognition, item-specific PI absent	letters
Postle & D'Esposito, 1999*	What-then-where delayed item recognition	Attneave shapes and locations
	Where-then-what delayed item recognition	locations and Attneave shapes
Postle, Berger, & D'Esposito, 1999	Delayed item and ordinal position recognition for 2 items	letters
	Delayed item and ordinal position recognition for 5 items	letters
	Delayed item and alphabetically reordered position recognition for 5 items (a.k.a. *manipulation*)	letters
Postle, Berger, Taich, & D'Esposito, 2000	Endogenously generated 2-D saccades	none
	Visually guided 3-D saccades	locations highlighted from an irregularly arranged array
	Delayed item and ordinal position recognition	locations highlighted from an irregularly arranged array
	Delayed item and geometrically reordered position recognition (a.k.a. *manipulation*)	locations highlighted from an irregularly arranged array
Postle, Berger, Goldstein, Curtis, & D'Esposito, 2001	Updating, 4-item trial	letters
	Updating, 8-item trial, group integrity preserved†	letters
	Updating, 8-item trial, group integrity preserved, within-trial item-specific PI†	letters
	Updating, 8-item trial, group integrity violated†	letters
	Updating, 8-item trial, group integrity violated, within-trial item-specific PI†	letters
	Updating, 12-item trial, group integrity preserved‡	letters
	Updating, 12-item trial, group integrity preserved, within-trial item-specific PI‡	letters
	Updating, 12-item trial, group integrity violated‡	letters
	Updating, 12-item trial, group integrity violated, within-trial item-specific PI‡	letters
Postle, Druzgal, & D'Esposito, 2003	AA delayed item recognition (i.e., one delay epoch)	faces
	ABA delayed item recognition (i.e., two delay epochs)	faces
	ABBA delayed item recognition (i.e., three delay epochs)	faces
Postle & D'Esposito, 2003	Delayed item recognition	egocentric location
	Delayed item recognition	allocentric location

*Only behavioral data from this study were reanalyzed. †These trials were evenly divided between those featuring 4 or 5 stimulus presentation epochs. ‡These trials were evenly divided between those featuring 6 or 7 stimulus presentation epochs.

curred, even though the three trial types were known to produce different levels of activity as a function of trial epoch and brain area. This characteristic of the recoded data was expected to decrease the sensitivity of our analyses, but not to bias our results in any direction, because the randomization of trial type across blocks ensured that this task-induced noise would be evenly distributed across trial position.

Behavioral data. Mean RT as a function of trial position was calculated for each participant by collapsing across blocks. These averaged time series were then normalized by subtracting from each data point the mean RT of the averaged time series. Thus, the mean normalized behavioral time series for each participant was 12 data points long and was centered on a value of 0. Reasoning that one behavioral manifestation of a buildup of item-nonspecific PI would be an increase in RT as a function of trial position, we tested for the simplest quantifiable monotonic function—a linear trend in the group average behavioral data—using the multivariate analysis of variance (MANOVA) framework. (Regression was not feasible because of the repeated measures aspect of the data. Note that we did not place any theoretical significance in this effect's being linear per se [e.g., Gorfein, 1987, summarizes evidence for nonlinear effects of item-nonspecific PI on behavior]; we simply reasoned that this contrast would be the most sensitive probe for detecting an effect of item-nonspecific PI in so inherently noisy a data set.) Were this analysis to yield a reliable result, we would also recode the RT data as a function of trial position within the experiment (i.e., 1–96) and assess the evidence for a trend across the entire length of the experiment.

fMRI data. Processing and statistical analyses were implemented with VoxBo neuroimaging analysis software (http://www.voxbo.org) running on Pentium PC Linux workstations. Our reanalyses began with data sets that had already gone through reconstruction, slice acquisition correction, motion compensation, and motion correction, as described in the original reports. The data were neither smoothed nor normalized. We parcellated the PFC into anatomically defined regions of interest (ROIs) corresponding to the right and left dorsolateral PFC (rdlPFC and ldlPFC), the right ventrolateral PFC (rvlPFC), and the portion of the left anterior inferior frontal gyrus (laIFG) corresponding to BA 45. The rdlPFC and ldlPFC ROIs, corresponding to BAs 9 and 46 in the respective hemispheres, incorporated a portion of the superior frontal gyrus, the middle frontal gyrus, and an anterior portion of the inferior frontal gyrus. The rvlPFC ROI, corresponding to BAs 44, 45, and 47, incorporated the portion of the inferior frontal gyrus posterior to Area 46 and anterior to the precentral sulcus. The laIFG ROI corresponded to the pars triangularis of the inferior frontal gyrus—that is, the portion rostral to the ascending ramus of the sylvian fissure and dorsal to the horizontal ramus of the sylvian fissure (Damasio, 1995). (The pars triangularis is bounded by the pars opercularis, which corresponds to BA 44, at its posterior extent and BA 46 at its anterior extent.) Finally, we defined an ACC ROI, corresponding to

BAs 24 and 32 bilaterally, which comprised the portion of the cingulate gyrus bounded, at its dorsocaudal extent, by the intersection of the paracingulate sulcus with the cingulate gyrus and, at its rostroventral extent, by its subgenual terminus.

The design of each of the five tasks permitted the fMRI signal evoked by each of the three epochs of the working memory task to be isolated and estimated directly, with minimal contamination by signals attributable to the other epochs in the trial (Postle, Zarahn, & D'Esposito, 2000; Zarahn, Aguirre, & D'Esposito, 1997b). Thus, we assessed evidence for trial-position–related trends in the signal attributable to the delay and the probe epochs, within each participant's data, within each of the ROIs. (Note that for the updating study [Postle et al., 2001], the *delay* signal was not process pure, because each stimulus presentation epoch engaged encoding and reordering processes in addition to those related directly to retention in memory. This did not affect our theoretical goal, however, which was to determine whether item-nonspecific PI-related effects were restricted to the probe epoch or also were present in other epochs of the trial.) A finding that such trends were evident only in the probe epoch would be interpreted as evidence that a phasically activated mechanism mediates the effects of item-nonspecific PI. A finding that such trends were also evident in the delay epoch, in contrast, would be interpreted as evidence that the buildup of item-nonspecific PI engages a mechanism that is active during many phases of the working memory task. In the event of the latter outcome, the mechanism of PI resolution might be either tonically active or phasically activated by any processing of an interfering stimulus, whether it be during encoding, rehearsal (e.g., Meyer, Glass, Mueller, Seymour, & Kieras, 2001), or probe evaluation.

The independent variables entered into the modified GLM (Worsley & Friston, 1995; Zarahn, Aguirre, & D'Esposito, 1997a) coded the data by epoch (i.e., target, delay, or probe) and by trial position within the block (i.e., 1–12). Low-frequency drift was accounted for in the design matrix (i.e., *detrending*) with scan effect covariates. That is, we removed the effects of any possible offsets between scans. Unlike with conventional event-related analyses (Postle, Zarahn, & D'Esposito, 2000), however, we did not include trial effect covariates, because the possible existence of offsets between trials within each scan could be the result of a tonically active PI resolution mechanism. Thus, neither our preprocessing nor our analysis methods biased our analyses in favor of detecting either phasic or tonic effects of item-nonspecific PI. Effect sizes were expressed as t values (parameter estimates divided by the residual error term from the solution of the GLM). The t values derived in this manner can be used as normalized indices of effect size, because the residual error term that makes up the denominator of the t value is positively, linearly related to the same scaling factor (or *gain effect*) that characterizes differences in overall BOLD signal intensity across scanning sessions (i.e., across participants). Indeed, t values may account for more unexplained interparticipant variance than do percentage of signal change measures (Postle, Zarahn, & D'Esposito, 2000), thereby increasing the sensitivity of random-effects group analyses. (Note that within a voxel or an ROI, a change in t value as a function of trial position cannot be attributable to an increase or decrease in variance as the block progresses, because there is only one error term associated with the solution of the GLM at any one voxel, and this does not change as a function of trial position.)

Each of two group analyses—one assessing linear trends in each ROI, the second assessing differences between ROIs—was performed separately for delay and probe epochs. Each of the two group analyses was implemented in three stages, the first two stages being common to both. First, we identified voxels within each ROI that were active during the epoch in question with a contrast that assigned weights of +1 to each of the 12 covariates modeling that epoch (i.e., a main effect of epoch). Second, we created ROI average time series by pooling across voxels identified in the first stage and determined the epoch-evoked response in each ROI for each trial position. In the *linear trends group analysis*, the third stage consisted of averaging the ROI average time series data across participants and, as with the behavioral data, testing for a linear trend using the MANOVA framework. In the *differential effects group analyses*, the third stage consisted of determining the slope of the best-fitting line for each ROI average time series from the second stage and entering these slopes as dependent data into a 2×4 fixed effects ANOVA with the factors of epoch (delay or probe) and ROI (rdlPFC, ldlPFC, rvlPFC, or laIFG). It was this analysis that would implement a critical test of the common-processes hypothesis—that the laIFG would respond differently to item-nonspecific PI than would other PFC ROIs. A fixed effects model was selected for this analysis because, had we employed a repeated measures analysis, missing values for individual ROIs from many of the data sets would have drastically limited the number of data sets entered into this third-stage analysis.

Results

Behavioral Data

The group RT data, coded as a function of trial position within the block, revealed an increasing monotonic trend that could be fit with a line with a slope of 4 msec/trial position [$F(1,33) = 10.16, p = .005; r^2 = .24$; Figure 1A]. Data restricted to the only study in which no stimulus appeared in more than one trial (Postle et al., 2003) also yielded a positive trend ($y = 1.78x + 648$ msec; data not mean centered). When the RT data were recoded as a function of trial position within the experiment (i.e., 1–96), they revealed a negative trend that could be fit with a line with a slope of −0.63 msec/trial position [$F(1,33) = 4.14, p = .05; r^2 = .11$] (Figure 1B). Thus, the RT data can be thought of as following a downward-sloping sawtooth pattern, with higher frequency, block-long trends of increasing RT superimposed on a lower frequency, session-long trend of decreasing RT. We interpreted these results as consistent with the presence of item-nonspecific PI in these data, an assumption that we pursued further in Experiment 2.

fMRI Data

Linear trends group analysis. Plotting the group average ROI average time series revealed that activity in many ROIs demonstrated a negative trend across trials within the block (Figure 2). Table 2 summarizes the quantification of these trends, revealing significant or borderline significant negative linear components in the activity of all ROIs during at least one of the two epochs examined, with the exception of the laIFG. Only the slopes of the best-fitting lines to time series from both epochs for the laIFG, as well as those from the probe epoch for the ldlPFC and the delay epoch for the ACC, were numerically, although not reliably, positive.

We did not expect to find that decreases in activity as a function of trial position would be the modal trend in the PFC. Was this a reflection of a *default* property that was characteristic of the entire brain, or was it unique to these PFC ROIs? The answer to this question would have implications for how we could interpret the fact that the laIFG seemed to differ from much of the rest of the PFC,

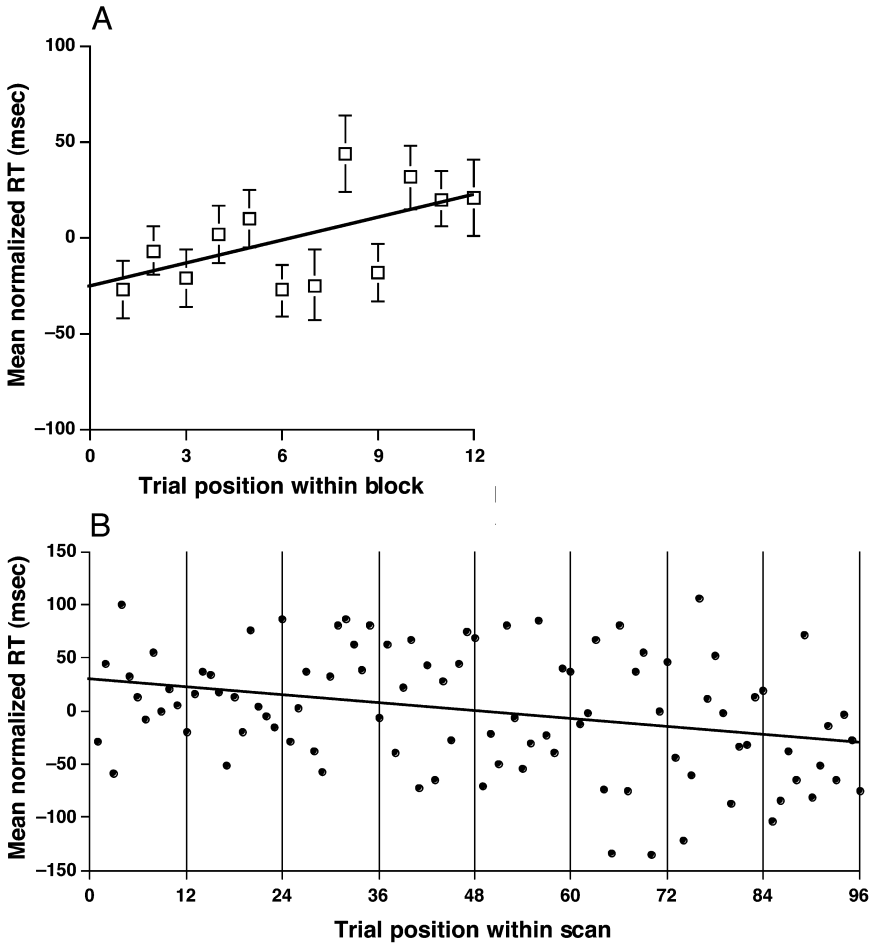

Figure 1. (A) Mean normalized reaction time (RT) data from Experiment 1, collapsed across blocks, as a function of trial position ($N = 34$). The equation describing the best-fitting line is $y = 4x - 26.1$. Error bars represent standard errors of the means. (B) Mean normalized RT data from Experiment 1 as a function of trial position within the experiment ($N = 34$). Vertical lines illustrate the boundaries between blocks. The equation describing the best-fitting line is $y = -.63x + 29.8$.

in that it did not demonstrate this pattern. Therefore, we investigated this pattern further by collapsing across all the voxels of the brain from each participant, thereby creating a single *global* ROI for each participant, then applying the methods of the *linear trends group analysis*. The results indicated that there was no significant trend during the delay epoch (slope = .005) [$F(1,23) = .05$, n.s.], but that there was a reliable negative trend during the probe epoch (slope = −.46) [$F(1,23) = 5.33$, $p < .05$; $r^2 = .19$] (Figure 3). Note that because our analysis removed the influence of trends that could produce dc shifts between scans, this effect can be explained only by factors operating within each scan (i.e., within each block of trials).

Differential effects group analyses. The fixed effects ANOVA assessing the slopes of linear fits to time series from the PFC ROIs revealed no main effect of epoch [$F(1,160) = 0.94$, n.s.], a main effect of ROI [$F(3,160) = 2.55$, $p = .05$], and no interaction [$F(3,160) = 1.44$, n.s.]. The planned follow-up contrast that also treated participant as a fixed effect indicated that the slope for the laIFG was significantly different (i.e., more positive) than those for the remaining PFC ROIs [$t(159) = 1.96$, $p = .05$].

Prompted by the results from the global ROIs, we performed additional post hoc comparisons of activity from the global ROIs versus the PFC ROIs. Excessive missing values from the delay epoch precluded the ability to perform a repeated measures ANOVA that included epoch as a factor. Within the delay epoch, pairwise contrasts indicated that none of the mean delay epoch trends for any of the ROIs differed significantly from the mean delay epoch slope of the global ROI. An ANOVA of probe epoch trends by ROI (including the global ROI), in contrast, yielded a significant main effect [$F(5,100) = 2.3$, $p = .05$], and pairwise contrasts confirmed that the probe

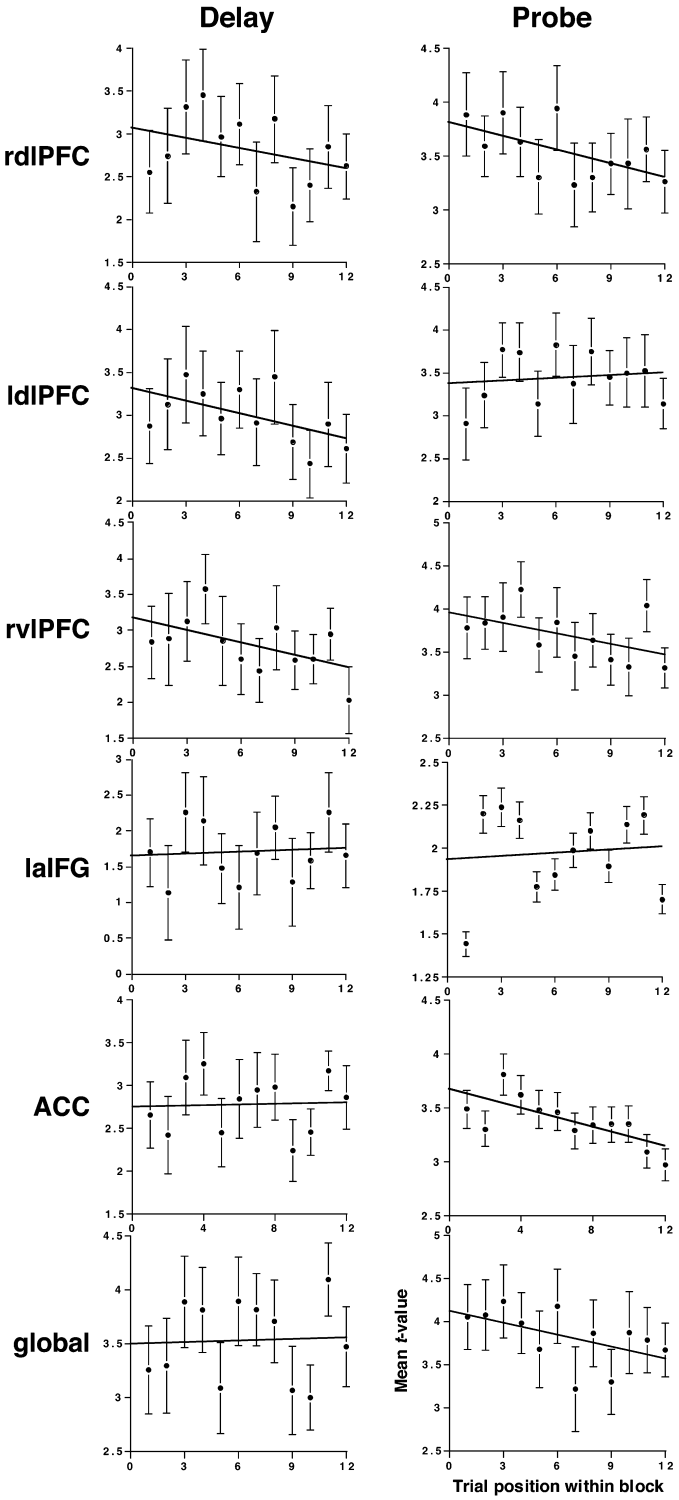

Figure 2. Mean evoked responses by epoch and by region of interest in Experiment 1. Slopes for each of the best-fitting lines and significance of these linear fits are given in Table 2. *N* contributing to each plot can be inferred from the degrees of freedom, also provided in Table 2. Error bars represent standard errors of the means. rdlPFC, right dorsolateral prefrontal cortex; ldlPFC, left dorsolateral PFC; rvlPFC, right ventrolateral PFC; laIFG, left anterior inferior frontal gyrus; ACC, anterior cingulate cortex.

Table 2
Linear Fits to fMRI Evoked Responses as a Function of Trial Position Within the Block, by Epoch

	Delay		Probe	
Area	Slope (*t* Value/Trial)	Linear Fit	Slope (*t* Value/Trial)	Linear Fit
rdlPFC	−.040	$F(1,18) = 2.24$, n.s.	−.042	$F(1,23) = 3.61$, $p = .07$; $r^2 = .14$
ldlPFC	−.049	$F(1,19) = 5.18$, $p < .05$; $r^2 = .21$	.011	$F(1,21) = 0.018$, n.s.
rvlPFC	−.058	$F(1,17) = 5.50$, $p < .05$; $r^2 = .24$	−.041	$F(1,23) = 3.45$, $p = .08$; $r^2 = .13$
laIFG	.010	$F(1,9) = 0.02$, n.s.	.007	$F(1,22) = 0.021$, n.s.
ACC	.004	$F(1,17) = 0.02$, n.s.	−.044	$F(1,21) = 3.09$, $p = .09$; $r^2 = .13$

Note—Missing data from the regions of interest of some participants resulted in different *N*s for each contrast (see the text for details). rdlPFC, right dorsolateral prefrontal cortex; ldlPFC, left dorsolateral PFC; rvlPFC, right ventrolateral PFC; laIFG, left anterior inferior frontal gyrus; ACC, anterior cingulate cortex.

epoch trends in both left-hemisphere PFC ROIs differed from the probe epoch trend of the global ROI [ldlPFC, $t(20) = 2.39$, $p < .05$; laIFG, $t(22) = 2.68$, $p < .05$].

Discussion

Interpreted from the perspective of the common-processes hypothesis that motivated this study, the results were broadly consistent with the prediction that the portion of the laIFG corresponding to BA 45 is differentially sensitive to item-nonspecific PI. The behavioral data revealed a significant increasing trend in RT within blocks of trials, a result consistent with a gradual buildup of item-nonspecific PI. This within-block trend occurred despite an overall trend of decreasing RT across all 96 trials of the experiment. The fMRI results indicated that the probe epoch activity of two subregions of the PFC—the laIFG and the portion of the left MFG corresponding to BAs 9/46—differed significantly from all other PFC ROIs, as well as from the global signal, in that they did not demonstrate a trend of decreasing probe epoch activity as a function of trial position. Similar-looking flat trends were also observed during the delay epoch in the laIFG and the ACC, but these occurred against a backdrop of a flat trend in the delay epoch global signal.

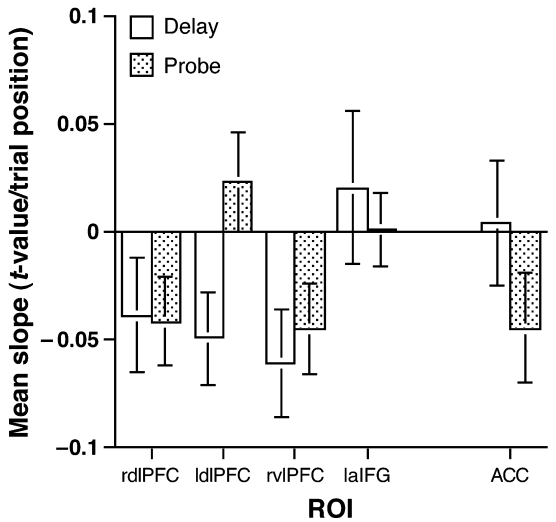

Figure 3. Mean slopes of best-fitting lines to block-averaged time series, by epoch and by region of interest (ROI) in Experiment 1. Data for PFC ROIs represent the data assessed in the differential-effects group analyses. Error bars represent standard errors of the means. rdlPFC, right dorsolateral prefrontal cortex; ldlPFC, left dorsolateral PFC; rvlPFC, right ventrolateral PFC; laIFG, left anterior inferior frontal gyrus; ACC, anterior cingulate cortex.

In view of the post hoc nature of our analyses, it is not surprising that they produced some unexpected results and others that lend themselves to alternative explanations. We will first consider the negative trend that we observed in the fMRI global signal during the probe epoch. This trend was not expected, and indeed, the trends in the global signal during both epochs that we investigated have implications for our interpretations of our results. Notably, because the insensitivity of the delay period global signal to trial position mirrors what we also observed in the laIFG and the ACC, we cannot draw any strong interpretations about the activity of these ROIs during this epoch in terms of sensitivity to item-nonspecific PI. Furthermore, this leaves us unable to assess questions about the time course of the hypothesized item-nonspecific PI-mediating mechanism, because they hinged on whether sensitivity to PI would be observed during both the delay and the probe epochs (consistent with a tonic or a phasic mechanism) or only during the probe epoch (consistent only with a phasic mechanism). Independent of its implications for our investigation of PI, this negative trend in probe epoch activity of the global signal is, in and of itself, a novel and potentially interesting phenomenon. For starters, the fact that we came across it in a retrospective reanalysis of five different data sets raises the question of whether it may be present in all of the hundreds of previously published neuroimaging studies of delayed-recognition working and short-term memory. Note that this effect would not have been detected in a typical event-related analysis, because trial averaging is typically performed according to independent variables that are distributed randomly throughout each block. It would also not be detected by a *mixed-block/event-related* design (Visscher et al., 2003), because this effect was *transient* in that it was restricted to the probe epoch and, thus, did not represent a *sustained* decline in baseline level of activity across trials. The fact

that it occurred beyond any nonspecific low-frequency drift that may have underlain the grand average time series indicates that it reflected a probe epoch effect that, on aggregate, declined across trials within each block. As we observed earlier, it is difficult to reconcile this effect with a fatigue account, although a gradual decline in attentional focus might manifest itself in this manner. Another possible explanation is that the default trend in the brain, at least during the probe evaluation/response components of working memory tasks, is for the evoked response to repeated trials within a block to gradually decrease, perhaps due to nonspecific physiological and/or psychological factors (e.g., Raichle et al., 1994). Finally, it could also reflect some general form of learning or habituation associated with certain features of the probe epoch of the item recognition task, such as motor preparation and/or execution.

Another unexpected feature of our results, perhaps related to the negative trend in the global signal, was the flat trend observed in the left PFC ROIs. Our a priori assumption had been that the neural correlate of the mediation of item-nonspecific PI would be an increase in signal as a function of trial position, analogous to our assumption about the RT correlates of item-nonspecific PI. So how can we reconcile our expectation with the actual results? Our tentative, highly speculative suggestion calls upon the negative trend considered in the previous paragraph. Implicit in our initial assumption about the sensitivity of the laIFG to item-nonspecific PI was the additional assumption that the default trend in brain activity would be flat. If, however, a negative trend is characteristic of all brain areas, including the left PFC, this might have the effect of masking the PI-related response of regions involved in the mediation of item-nonspecific PI. Specifically, the positive PI-related trend that is a true component of the signal in these regions might sum with the negative default trend to yield an aggregate trend that does not vary with trial position—a flat line.

Next, we turn to possible alternative explanations of the RT results. Their interpretation is central to this enterprise, because we rely on them to index the presence of item-nonspecific PI. The questions raised by this discussion will motivate Experiment 2, a prospective study of the effects of item-nonspecific PI on RT. To foreshadow, the results of Experiment 2 will bolster our confidence that the RT data from Experiment 1 do, indeed, index item-nonspecific PI. The General Discussion section, then, will proceed with a consideration of the nature and possible functional significance of the negative trend in probe-evoked activity in the global signal. Finally, we will assess the implications of the results of this study for the common-processes hypothesis and for our understanding of the mediation of item-nonspecific PI.

There are two salient possible objections to our interpretation of the RT data as behavioral evidence of a buildup of item-nonspecific PI. The first is that inspection of Figure 1A indicates that there is considerably more variability in the second half of the block-averaged time series, with the means for Trials 6, 7, and 9 looking little different from the mean for Trial 1. Does this mean that the trials in the second half of the block were, on average, insensitive to the buildup of item-nonspecific PI? And if so, does this create a problem for our preferred interpretation of these data? Our answer to the first question is *perhaps*, and our answer to the second question is *no*. The classic literature on the temporal dynamics of item-nonspecific PI, as measured with the Brown–Peterson task, indicates that the effects of item-nonspecific PI typically asymptote within the first three or four trials in a block (as reviewed, e.g., by Gorfein, 1987), and thus, the increased variability in RTs in the second half of the block in our data is not surprising. Furthermore, it was not theoretically important to this study that the sensitivity of RT to PI be linear per se, just that we observe evidence of an increase as a function of trial position for the first few trials of the block.

A second possible objection to our interpretation of the RT data is more fundamental. It asserts that the increase in RT as a function of trial position may just as easily be explained as an effect of fatigue or of flagging attention, which builds up across a block and "recovers" during the breaks that occur between scans. Because these alternatives cannot be ruled out with the design and data presented thus far, we implemented Experiment 2 to address them. Nevertheless, we feel comfortable provisionally interpreting our data in the context of item-nonspecific PI, for two reasons. First, the overall trend of decreasing RT across all 96 trials of the experiment indicates that, at this larger temporal window, there is no evidence for fatigue or waning attention. Second, the fMRI data do not readily support these alternatives. For example, the global signal plotted as a function of trial position was flat during the delay epoch and significantly negative during the probe epoch. Thus, a fatigue account would have to posit that one or both of the PFC ROIs that did not follow the trend of the global signal during the probe epoch was differentially sensitive to fatigue, a possibility that we find much less plausible than the PI account. A waning attention account would need, in addition, to explain why the global trend did not also decrease during the delay period. Regardless of the strength of this reasoning, however, a strong interpretation of the results of Experiment 1 depended on our ability to demonstrate, with an independent data set, that item-nonspecific PI produces a pattern in RTs that resembles that illustrated in Figure 1A.

EXPERIMENT 2

The two data sets described here were generated to address two concerns about the interpretation of the RT data from Experiment 1: the increased variance in RTs from trials occurring in the second half of the block, and non-PI (i.e., fatigue and/or waning attention) alternative explanations of the positive linear trend.

Experiment 2A

This experiment served to assess the replicability of the pattern observed in the RT data from Experiment 1—a steady increase as a function of trial position during the first several trials of the block, but increasing variability, and perhaps a flattening out, during the second half of the block. These data were produced by participants performing an fMRI study that was designed to test, in a prospective manner, the hypotheses introduced in the present report (Brush & Postle, 2003) and by participants performing a behavioral study employing procedures that simulated fMRI scanning conditions. (Only the behavioral data from the fMRI study are presented in this report.) Although the present experiment featured far fewer participants than did Experiment 1, patterns in its results were expected, in principle, to be easier to interpret than those in Experiment 1, because of its prospective nature. Importantly, Experiment 2A was designed to emphasize item-nonspecific PI by changing stimulus domain with each block of trials. Such a change of stimulus type was expected to produce a release from item-nonspecific PI.

Method

Participants. The RT data from 16 participants (9 females) in the fMRI study were supplemented with data from 5 additional individuals (3 females) who participated in a behavioral study that simulated conditions of the fMRI laboratory. Participant age ranged from 18 to 32 years, and all reported themselves free of any history of neurological or psychiatric illness and not to be taking any prescription medication. All gave informed consent.

Materials. The experiment featured stimuli drawn from seven stimulus domains: letters (the 21 consonants, including *y*), color patches (red, pink, orange, yellow, green, light blue, indigo, purple, white, and gray), locations (16, each identified by a white circle and centered in one of the 16 rectangles produced by dividing the screen with three equally spaced vertical lines and three equally spaced horizontal lines), names of flowers (16 of the 19 most frequently named flowers as listed in the norms of Battig & Montague, 1969), digits (0–9), faces (16 grayscale male faces), and polygons (16 drawn from those in Attneave & Arnoult, 1956, that were determined by normative testing to be difficult to name [Vanderplas & Garvin, 1959]).

Procedure. Trial structure and experimental design were procedurally similar to those in D'Esposito et al. (1999). The stimuli were blocked by domain, and each block featured 16 delayed-recognition trials. To simplify comparison with the data in Experiment 1, only the results from the first 12 trials of each block are presented here. Within each block, a preliminary stimulus order was determined randomly without replacement, with the pool of potential stimuli being replenished each time it was exhausted. This order was then modified where needed to create high-overlap trials. (Results pertaining to item-specific PI are not presented here.) Each trial began with the presentation of either one or four memoranda (one face and one shape target; four color, digit, word, location, and letter targets) for 1,000 msec (with the exception of the words, which were presented for 1,500 msec). Four-item target sets (with the exception of location stimuli) were presented equidistant from a central fixation cross, so that each was centered at a corner of an imaginary square that was itself centered on the screen. All the stimuli were white (excluding colors) and were presented against a black background. Each block began with instructions identifying the type of stimuli that would be presented, followed by a 20-sec delay with a blank screen. All trials lasted 8 sec from target onset to probe onset, with an intertrial interval (ITI) of 13 sec. Block order was pseudorandomized, with the constraint that no two blocks of overtly verbalizable material (i.e., words, digits, or letters) were presented consecutively. The participants were assigned to one of three different block orders in the experiment.

The behavioral testing was performed in a darkened room and with precisely the same timing parameters as those used in the fMRI study. Between blocks, the experimenter and the participant sat quietly, with the lights remaining off, for approximately 60 sec before the start of the next block.

In addition to stimulus type, degree of probe overlap (high or low) was manipulated within each block. Nine of the 16 probes in each block were negative, and 7 were positive. Of the 9 negative probes, 5 were high overlap, meaning that the probe of trial n matched a target item from trials $n-1$ and $n-2$ (in the case of four-target item blocks) or the target from the $n-1$ trial (in the case of one-target item blocks). Low-overlap probes did not match any items in the previous two target sets. All the positive trials featured low overlap.

Results

The results displayed a pattern that was qualitatively similar to that seen in Experiment 1: an increase across the first 5 trials, followed by a flattening out of the trend, with a comparable number of the final 7 trials falling on each side of the block-averaged mean (Figure 4). The test for a linear trend across all 12 trials yielded a nonsignificant result [$F(1,20) = 0.01$, n.s.]. The mean RTs from the first 5 trials of the block, however, could be fit with a line whose mean slope was 27.10 msec/trial ($SE = 8.25$), a value that was significantly greater than the slope of 8.03 msec/trial ($SE = 5.15$) obtained from the first 5 trials of the block-averaged data in Experiment 1 [$t(53) = 2.07$, $p < .05$].

Discussion

The results from Experiment 2A replicated, in a qualitative sense, the pattern observed in Experiment 1. In

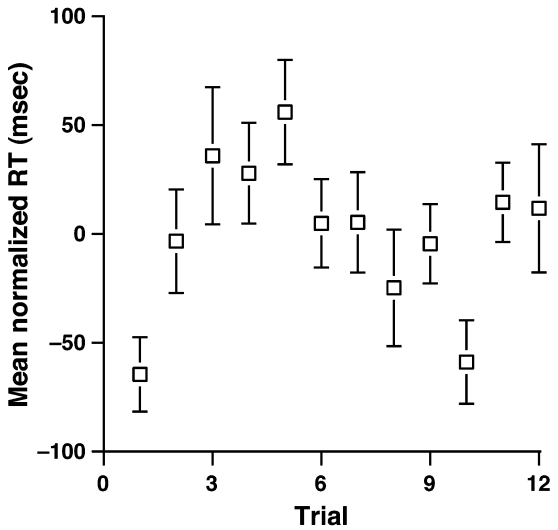

Figure 4. Mean normalized reaction time (RT) data from Experiment 2A, collapsed across blocks, as a function of trial position ($N = 21$). Error bars represent standard errors of the means.

particular, both studies yielded RTs that increased across the first five trials of the block before flattening out. The quantitative difference in the slope of the initial portion of these two functions may be attributable to the fact that stimulus domain changed from block to block in Experiment 2A, thereby producing a greater release from PI. Although the results from Experiment 2A did not permit us to address decisively the competing explanations of the RT pattern in Experiment 1, they gave us license to design an experiment that would.

Experiment 2B

This experiment was designed to produce a buildup of item-nonspecific PI that could not be confounded with fatigue or attentional effects. It did so by grouping trials of a particular stimulus domain so that transitions from one domain to another occurred within blocks, as well as between them. Within-block transitions would produce a release from item-nonspecific PI—and a subsequent buildup—that would not be confounded with fatigue or waning attention.

Method

Participants. Twenty-four undergraduates participated, and all gave informed consent.

Materials and Procedure. The stimuli were identical and the procedure similar to those in the behavioral tests of Experiment 2A, with the exception that each participant performed only three blocks, or 16 trials/block, and stimulus domain changed after 5–8 consecutive trials of the same type. Each change of stimulus type was preceded with an instructional message presented during the ITI that identified the upcoming stimulus type. (This emulated Experiment 2A, in which the identity of the upcoming block of trials was presented during each interblock interval.) Two of the three blocks contained one within-block stimulus change, and the other contained two, yielding a total of four within-block stimulus changes. Six forms of the task were produced so as to counterbalance order of trial and block type.

Results

RT data were averaged by aligning trials to the first trial in each group that produced a within-block change of stimulus type and discarding data from the sixth, seventh, and eighth trials of the stimulus group. The result was an increase in RT as a function of trial position that could be fit with a line whose mean slope was 8.66 msec/trial (SE = 5.6; Figure 5). This value did not differ from the mean slope of the first five trials in Experiment 1 [$t(57)$ = 0.08, n.s.].

Discussion

Experiment 2A confirmed that increases in RT as a function of trial position are observed only across the first several trials of the block, and Experiment 2B produced an item-nonspecific PI effect that was practically undifferentiable from the trend across the first five trials in Experiment 1. These results reinforce our interpretation that the RT effect that we observed in Experiment 1 was due, at least in part, to the buildup of item-nonspecific PI. Having strengthened our interpretation of the RT data, we can now turn to a consideration of the neural correlates of these data and to the theoretical implications suggested by the results in Experiment 1.

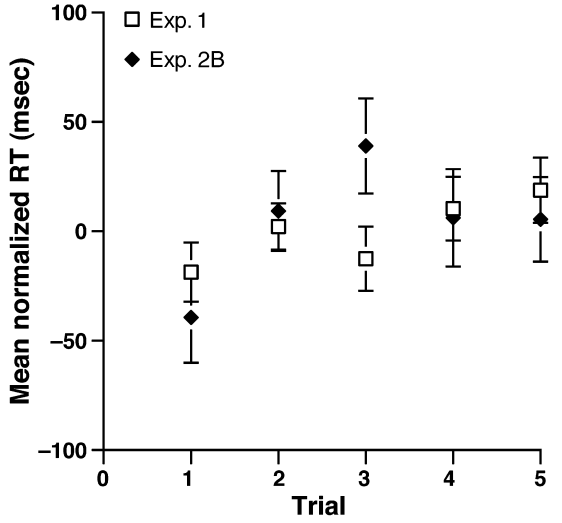

Figure 5. Overlay of the mean normalized reaction times (RTs) from the first five trial positions of Experiment 1 and from Experiment 2B. Error bars represent standard errors of the means.

GENERAL DISCUSSION

Our reanalysis of the behavioral and fMRI data from seven independent studies indicates that item-nonspecific PI, as indexed by increases in RT as a function of trial position, is associated with a differential pattern of probe-evoked activity in the laIFG and the ldlPFC. As such, these results provide preliminary support for the common-processes hypothesis. In addition, they provide an empirical basis for refining this hypothesis and for generating novel predictions about the neural bases of interference resolution. One question highlighted by our results is that of the regional specificity of frontal cortical sensitivity to item-nonspecific PI. We observed two ROIs, in addition to the laIFG, that also demonstrated activity that varied from the modal pattern of decreasing activity as a function of trial position: the ACC and the ldlPFC. In the ACC, this occurred during the delay epoch, an effect that is ambiguous with respect to item-nonspecific PI, because it mirrors the trend in the global signal during this epoch. In the ldlPFC, however, the numerically positive trend occurred during the probe epoch. Assuming that this effect, like the comparable one in the laIFG, is related to the mediation of item-specific PI, can it be reconciled with the common-processes hypothesis? We believe so and suggest that the key to predicting ldlPFC sensitivity to PI may be the extent to which the presence of PI is steady and/or predictable. This prediction follows from a review of previous results and how they compare with those in the present study.

In the study of item-specific PI that launched the current interest in this phenomenon—a blocked-design positron

emission tomography (PET) study—the activity associated with item-specific PI was most prominent in the laIFG, but it did extend dorsally into an adjacent portion of the ldlPFC (Jonides et al., 1998). This trend was echoed in a subsequent, procedurally identical blocked-design PET study of item-specific PI in older adults (Jonides et al., 2000). Inconsistent with an involvement of the ldlPFC in the resolution of item-specific PI, however, are the results of three event-related fMRI studies and of a study of the behavior of patients with focal PFC lesions. The fMRI studies identified sensitivity to item-specific PI in the laIFG, but not in other subregions of the PFC, including the ldlPFC (in two studies, the source of the PI was in the previous trial [D'Esposito et al., 1999; Nelson et al., 2003], and in the third study, which employed an updating task, it was earlier in the same trial [Postle et al., 2001]). The neuropsychological study indicated that whereas a patient whose damage encompasses all of the pars triangularis of the laIFG showed significantly greater sensitivity to item-specific PI than did age-matched control participants, several other patients whose lesions affected the ldlPFC, but spared the critical portion of the laIFG, showed normal sensitivity to item-specific PI according to these two measures (Thompson-Schill et al., 2002). The most obvious factor differentiating the two PET studies from the fMRI and neuropsychological studies is experimental design. The former employed blocked presentation of trials featuring either a high or a low proportion of item-specific PI-producing probes, whereas the latter randomized the order of trials according to this factor. Thus, one possible account of the pattern of results reviewed here, together with the results of the present study, is that the phasic resolution of PI produced by unpredictably occurring high-overlap probes is supported by the laIFG, whereas the resolution of PI that is more predictable and that can be present across consecutive trials (i.e., as a steady state) may recruit a larger cortical network that also encompasses more dorsal regions of the left PFC. At the computational level, this idea may be similar to that of *proactive versus reactive* control (Burgess & Braver, 2004). Testing this idea will require a design that assesses the effects of both item-specific PI procedures (blocked vs. randomized) and item-nonspecific PI in the same participants. Were this hypothesis to be validated, an important question would be whether such recruitment of a broader network reflects expansion of a process *centered* in the laIFG or the recruitment of a second, distinct process.

Throughout this report we have made the assumption that there exists a set of control processes whose functions include the mediation of the effects of item-nonspecific PI. Indeed, we have interpreted PI-related trends in the fMRI signal as neural correlates of these control processes. A priori, this does not need to be the case. The behavioral and neural effects of item-nonspecific PI could just as well reflect the fact that the presence of PI requires cognitive processes to work harder and for a longer period of time. Thus, the effects of increasing the duty cycles of, say, probe evaluation processes (e.g., Ratcliff, 1978; Sternberg, 1966) might be to increase RT and the neural activity evoked by these processes. There is less uncertainty about the existence of control processes in the mediation of item-specific PI, however, due to a convergence of behavioral, neuroimaging, and neuropsychological data that address this question: A robust item-specific PI-related signal in left BA 45 is observed in healthy young participants whose item-specific PI-related RT cost is modest, whereas this neural signal is missing in healthy elderly participants for whom the behavioral effect is much larger (Jonides et al., 2000), and a patient with a circumscribed PFC lesion that includes left BA 45 shows a dramatically higher behavioral sensitivity to item-specific PI (but not to low-PI conditions) than do PFC-lesioned control participants whose damage spares this critical region (Thompson-Schill et al., 2002). Thus, a potentially important theoretical implication of the common-processes hypothesis might be that the presence of item-nonspecific PI also recruits PI-mediating control processes.

Following the reasoning laid out in the previous paragraph, the common-processes hypothesis may also serve to impose constraints on theoretical accounts of the effects of normal aging on working memory performance. For example, the *duty cycle* alternative considered above can also account for the data on the effect of aging on working memory span (Lustig et al., 2001; May et al., 1999). It does so by positing that a decline in the effectiveness of memory-encoding processes in the healthy elderly renders memory retrieval processes more susceptible to the degrading effects of PI. The details come from Jonides et al. (2000), who noted that normal aging may lead to decreased effectiveness with which encoding processes incorporate into mnemonic representations a contextual tag that identifies these representations as corresponding to the current trial (Monsell, 1978). And because "[a] decline in accurate coding of the temporal context for a target item will render the decision about whether that item is a member of a recent target set more difficult" (Jonides et al., 2000, p. 194), an age-related decline in working memory performance could result without the need to invoke a decline in a PI-mediating control process, such as inhibition. Affirmative evidence for the common-processes hypothesis, however, would rule out an encoding-related account as the sole explanation of the effects of aging on working memory performance, because encoding processes do not seem to be implicated in item-specific PI-related effects.

The research summarized in this report is consistent with a common-processes view of the mediation of item-specific and item-nonspecific PI. Future work will need to address several important questions, including the precise relationship between behavioral and neural indices of item-nonspecific PI, the degree of overlap in the laIFG of voxels sensitive to the two sources of PI, and the role of expectancy in shaping the neural response to PI.

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